ArcticNet ᐅᑭᐅᖅᑕᖅᑐᕐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ

Impacts of Environmental Change in the Canadian Coastal Arctic

A Compendium of Research Conducted during ArcticNet Phase IV (2016–17)

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Mickaël Lemay, Ashley Gaden and Carl Barrette.

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ArcticNet is supported by the Government of Canada through the Networks of Centres of Excellence programs, a joint initiative of the Natural Sciences and Engineering Research Council, the Canadian Institutes of Health Research, the Social Sciences and Humanities Research Council and Industry Canada.

The Networks of Centres of Excellence are unique partnerships among universities, industry, government and not-for-profit organizations aimed at turning Canadian research and entrepreneurial talent into economic and social benefits for all Canadians. An integral part of the federal government's Innovation Strategy, these nation-wide, multidisciplinary and multisectorial research partnerships connect excellent research with industrial know-how and strategic investment.

The ArcticNet Network of Centres of Excellence was incorporated as a not-for-profit corporation under the name "ArcticNet Inc." in December 2003.

ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ ᐃᓂᖃᖅᑎᑕᐅᔪᖅ ᓚᕚ, ᑯᐸᐃᒃ ᓯᑎ, ᑲᓇᑕ

ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ ᐱᑕᖃᕈᓐᓇᖅᑎᑕᐅᔪᖅ ᑖᒃᑯᓇᙵᑦ ᑮᓇᐅᔭᒃᓴᖅᑎᑕᐅᓪᓗᓂ ᑐᑭᓯᒐᓯᐊᖃᑎᒌᑦ ᐱᑐᒃᓯᒪᓂᒃᑯᑦ ᑐᑭᓯᓐᓂᐊᖃᑎᒌᑦ ᐱᐅᓛᑦ ᑲᓇᑕᒥ, ᑲᑐᑎᔭᐅᓪᓗᓂ ᐱᓕᕆᐊᕆᔭᐅᔪᖅ ᑖᒃᑯᓇᙵᑦ ᓄᓇᒥᐅᑕᕐᓂᒃ ᖃᐅᔨᓴᐃᔨᒪᕆᑦ ᐊᒻᒪᓗ ᐃᑯ-ᒪᓕᕆᓂᕐᒥ ᖃᐅᔨᓴᖅᑎᑦ ᑲᑎᒪᔨᙱᑦ, ᑲᓇᑕᒥ ᐃᓕᓐᓂᐊᕐᕕᒃ ᐃᓅᓯᓕᕆᓂᕐᒥ ᖃᐅᔨᓴᐃᓂᖅ, ᐃᓅᓯᕐᒥ ᖃᐅᔨᓴᐃᓂᓪᒪᕆᒃ ᐊᒻᒪᓗ ᐃᓅᔾᔪᑎᓕᔪᓐᓇᖅᑕᑦᑎᒍᑦ ᖃᐅᔨᓴᐃᓂᖅ ᑲᑎᒪᔨᙱᑦ, ᐊᒻᒪᓗ ᐱᓇᓱᐊᖅᑐᓕᕆᓂᖅ ᑲᓇᑕ.

ᐅᑯᐊ ᐱᑐᒃᓯᒪᕝᕕᑦ ᐱᐅᓛᑦ ᑲᓇᑕᒥ ᐊᔾᔨᐅᙱᑦᑑᔪᒥᒃ ᐱᓇᓱᐊᖃᑎᒋᔭᙱᑦ ᐊᕙᑖᓂᑦ ᐃᓕᓐᓂᐊᕝᕕᒃᔪᐊᓂ, ᐱᓇᓱᐊᖅᑐᓕᕆᓂᖅ ᑲᓇᑕ, ᒐᕙᒪᒃᑯᑦ ᐊᒻᒪᓗ ᑮᓇᐅᔭᓕᐅᕐᓯᐊᕐᓂᒃ ᐊᐅᓚᑦᓯᔨᐅᔪᑦ ᑐᕌᖅᑐᑦ ᑐᓄᑎᒍᓐᓇᖅᓗᒍ ᑲᓇᑕᒥᐅᑦ ᖃᐅᔨᓴᖅᓂᙱᑦ ᐊᒻᒪ ᓇᖕᒥᓂᖅᑐᓕᕆᓂᖅ ᐱᓕᕆᐊᓇᖅᓯᐊᖅᑐᑦ ᑕᒪᑐᒧᖓ ᒪᑭᑕᓇᓯᐊᕐᓂᕐᒧᑦ ᐊᒻᒪᓗ ᐃᓅᓯᕐᒥ ᐃᑲᔫᑎᓂᐊᖅᑐᓄᑦ ᑕᒪᐃᓐᓄᑦ ᑲᓇᑕᒥᐅᓄᑦ. ᑕᐃᒪᓗ ᐃᓗᓪᓕᓇᓗᐋᖅᑕᖓ ᐃᓚᖓ ᒐᕙᒪᒃᑯᑦ ᓄᑖᓂᒃ ᐱᑎᐊᓪᓚᒍᑎᓕᓂᖅ ᐋᖅᑭᒃᓯᒪᐅᑎᖓᑦ, ᐅᑯᐊ ᑲᓇᑕᓕᒫᒧᑦ, ᐊᒥᓱᑦ ᐃᓂᖅᑎᓇᔪᓐᓇᖅᑐᑦ ᐊᒻᒪᓗ ᐊᒥᓱᑦ ᖃᓄᖅᑐᐃᓐᓇᕐᓂᒃ ᐱᓕᕆᐊᓇᖅᑕᑖᑦ ᑲᑎᙵᔪᑦ ᐱᐅᓂᖅᐹᖑᔪᒥᒃ ᖃᐅᔨᓴᐃᓂᕐᒥᒃ ᐱᓇᓱᐊᖅᑐᓕᕆᓂᕐᒥ ᖃᐅᔨᓴᖅᑕᐅᓕᕈᓐᓇᖅᑐᓂᒃ ᐊᒻᒪᓗ ᐋᖅᑭᒃᓯᒪᐅᑎᖏᑦ ᖃᑭᓯᐊᕈᑎᒋᔭᐅᖅᑐᓂᒃ.

ᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ ᐱᑐᒃᓯᒪᖃᑎᒋᔭᙱᑦ ᑖᒃᑯᓇᙵᑦ ᑐᑭᓯᒐᓯᐊᖃᑎᒌᑦ ᐱᑐᒃᓯᒪᓂᒃᑯᑦ ᐱᐅᓈᑦ ᑲᓇᑕᒥ ᑎᒥᙳᖅᑎᑕᐅᓯᒪᔪᑦ ᑮᓇᐅᔭᓕᐅᖅᑎᐅᓯᒪᐊᖑᑎᒃ ᑯᐊᐳᓴ ᐊᑖᒍᑦ ᐊᑎᖅᑲᖅᓗᑎᒃ "ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ ᑎᒥᖓ" ᑕᐃᑲᓂ ᑎᓯᐱᕆ 2003.

Le centre administratif d'ArcticNet se situe à l'Université Laval, Québec, Québec, Canada.

ArcticNet est appuyé par le Programme des Réseaux de centres d'excellence du Gouvernement du Canada, un projet conjoint du Conseil de recherches en sciences naturelles et en génie, des Instituts de recherche en santé du Canada, du Conseil de recherches en sciences humaines et d'Industrie Canada.

Les Réseaux de centres d'excellence constituent des partenariats uniques entre les universités, l'industrie, le gouvernement et les organismes à but non lucratif visant à transformer la recherche et le talent entrepreneurial canadien en avantages socio-économiques pour tous les Canadiens. Partie intégrante de la stratégie d'innovation du gouvernement fédéral, ces partenariats de recherche nationaux, multidisciplinaires et multisectoriels assurent la jonction d'une recherche de haut niveau avec un savoir-faire industriel et un investissement stratégique.

Le Réseau de centres d'excellence ArcticNet a été incorporé en tant qu'organisme à but non lucratif sous le nom « ArcticNet inc. » en décembre 2003.

Canada

Coming together in the study of a changing Canadian Arctic.

ᐊᐅᓪᓚᖃᑎᒌᒃᓯᒪᔪᑦ ᐃᓕᑦᑎᓇᓱᖃᑎᒌᒃᑐᒡᓗᑎᒃ ᐊᓯᑦᔩᑉᐸᓪᓕᐊᓂᖓᓂᒃ ᑲᓇᑕᐅᑉ ᐅᑭᐅᖅᑕᖅᑐᖓ.

Travailler ensemble à l’étude de l’Arctique canadien de demain.

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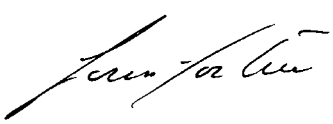
FOREWORD

The Arctic is the region of the globe most severely impacted by the present warming of Earth's lower atmosphere. Many of the symptoms of a warming Arctic anticipated by climate models have already been verified by observations on land, at sea and from space. As summarized in the Arctic Climate Impact Assessment (ACIA 2004), the multiple environmental, socio-economic and geopolitical perturbations taking place in the Arctic are interacting to bring about an irreversible transformation of the North. ArcticNet is a Network of Centres of Excellence jointly funded by the three Research Councils to help Canada prepare for the impacts of this transformation. The central objective of ArcticNet is to generate the knowledge and assessments needed to formulate adaptation strategies and policies that will help northern societies and industries to prepare for the full impacts of environmental, economic and societal changes in the coastal Canadian Arctic. Our vision is to build a future in which, thanks to two-way knowledge exchange, monitoring, modelling and capacity building, scientists and Northerners have jointly attenuated the negative impacts and maximized the positive outcomes of these changes. This compendium presents the advancements towards this vision that have been achieved over the second year of phase IV (2016-2017) of ArcticNet. We thank all of our network investigators, students, other researchers, colleagues and partners for helping ArcticNet attain its goals, and the ArcticNet compendium editorial team for bringing this document through to completion.

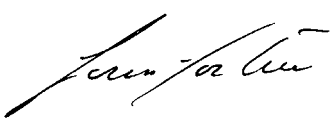
Louis Fortier, Scientific Director of ArcticNet



ᐱᒋᐊᕐᓂᖓ

ᐅᓇ ᐅᑭᐅᖅᑕᖅᑐᖅ ᓄᓇᖓ ᓄᓇᕐᔪᐊᒥ ᐊᒃᑐᖅᑕᐅᖄᕐᓂᐊᖅᑐᖅ ᐊᒻᒪ ᐊᖏᓛᖑᔪᒥᒃ ᓱᑯᑕᐅᓗᓂ ᑕᒪᑐᒪᖓᑦ ᓂᕆᐊᓂᒐᖅᑐᓂᑦ ᐅᖅᑰᓯᕙᓪᓕᐊᓂᖔᓄᑦ ᓄᓇᕐᔪᐊᑦ. ᐅᓄᖅᑐᑦ ᑕᒻᔭᐅᓕᖅᑐᑦ ᖃᐅᔨᑦᑎᔪᑦ ᐅᑭᐅᖅᑕᖅᑐᖅ ᐅᖂᓯᓂᖔᓄᑦ ᖃᐅᔨᔾᔪᑎᖃᖅᖢᓂᒃ ᓯᓚᐅᑉ ᖃᓄᐃᓐᓂᖓᓂᒃ ᓴᓇᕿᑕᐅᔪᓂᒃ ᓇ, ᓇᐃᖅᑐᖅ ᑕᑯᔭᐅᔪᖅ ᓄᓇᑐᐃᓐᓇᒥ, ᑕᕆᐅᕐᒥ ᐊᒻᒪ ᓄᓇᕐᔪᐊ ᓯᓚᑖᓂ. ᓇᐃᓈᖅᑐᒍ ᐅᖃᕈᓐᓇᖅᑐᒍᑦ ᐅᑭᐅᖅᑕᖅᑐᖅ ᓯᓚᒐᑕ ᐊᕙᑎᖓᑕ ᐊᔾᔨᕐᓂᖓ ᐊᒃᑐᖅᑕᐅᓂᖓᓂᒃ ᓱᕐᑯᐃᖅᑕᐅᓇᓱᒃᓯᒪᔪᓂᑦ 2004, ᐊᒥᓱᑦ ᐊᔾᔨᒌᙱᑦᑐᑦ ᓯᓚᓐᓂᐊᖅᑐᑦ, ᐃᓅᓯᓕᕆᓂᕐᒥᒃ ᑮᓇᐅᔭᑎᒍᑦ ᐱᕙᓪᓕᐊᓂᖅ ᐊᒻᒪ ᓄᓇᖏᓐᓄᑦ ᒪᕋᓕᕆᓂᖅ ᑕᒻᔭ ᐱᓕᕆᔭᐅᔪᑦ ᐅᑭᐅᖅᑕᖅᑐᒥ ᑕᐃᒪᓗ ᐊᔾᔨᒌᓂᐊᖅᑐᖅ ᑭᓱᖑᕐᓗᓂ ᐅᑎᕈᓐᓇᕐᓂᐊᙱᑦᑐᖅ ᐅᑭᐅᖅᑕᖅᑐᒥ ᑕᐃᒪᓐᓇᐅᖕᒥᓐᓇᐅᔭᓕᕐᓂᐊᖅᑐᑦ. ᐅᑭᐅᖅᑕᖅᑐᒥ ᑐᑭᓯᓐᓂᐊᖃᑎᒌᑦ ᓄᐊᑎᓇᕗᑦ ᖃᐅᔨᒪᔭᐅᔪᓂᒃ ᐊᒻᒪ ᓱᕐᑯᐃᖅᑕᐅᓯᒪᔪᓂᒃ ᑭᖕᖒᒪᕆᔭᐅᓯᒪᔪᓂᒃ ᐋᕿᒃᓯᓂᐊᕐᓗᑎᒃ ᓱᖕᕆᐅᑎᑦᑎᔾᔪᑎᒃᓴᐃᑦ ᐊᒻᒪ ᐊᑐᐊᒐᐃᑦ ᐅᑯᐊ ᐃᑲᔪᕐᓂᐊᖅᑐᖅ ᐅᑭᐅᖅᑕᖅᑐᒥᐅᓂᒃ ᐊᒻᒪ ᑲᒻᐸᓂᐅᔪᓂᒃ ᐱᓂᒃᓴᕇᖅᓯᒪᓗᑎᒃ ᐊᒃᑐᖅᑕᐅᓂᖓᕐᓂᖓᓄᑦ ᐊᕙᑎᖓᑦ ᐊᒻᒪ ᐃᓅᓯᖓᑦ ᐊᔾᔨᕐᓗᑎᒃ ᓯᓪᔭᖏᑦ ᑲᓇᑕᐅᑉ ᐅᑭᐅᖅᑕᖅᑐᐊᓂ. ᐅᓇ ᑕᐅᑦᑐᓇᔭᕗᑦ ᓴᓇᓗᒍ ᓯᕗᓂᒃᓴᕗᑦ, ᖁᔭᓐᓇᒦᒃ ᑕᒻᔭᐅᖕᒪᑦ ᑐᓴᐅᒪᖃᑎᒌᖕᓂᖅ ᖃᐅᔨᒪᖃᑎᒌᖕᓂᖅ, ᒥᐊᓂᕆᓂᖅ, ᐋᕿᒃᓱᐃᓂᖅ ᐊᒻᒪ ᐃᓗᓪᓕᖅᓱᐃᓂᖅ, ᖃᐅᔨᓴᖅᑎᒻᒪᕇᑦ ᐊᒻᒪ ᐅᑭᐅᖅᑕᖅᑐᒥᐅᑦ ᑲᑎᓯᒪᔭᖏᓐᓂᑦ ᐱᓕᕆᑦᑎᐊᖅᖢᑎᑦ ᐱᐅᓐᖏᑦᑐᑎᒃ ᐊᒃᑐᐃᓇᔭᓚᐅᖅᑐᓄᑦ ᐊᒻᒪ ᐊᖏᓪᓕᑎᓯᒪᓪᓗᒋᑦ ᐱᐅᔪᓂᒃ ᐊᑑᑎᖃᑦᑎᐊᖅᑐᓂᒃ ᐱᑦᑐᒍ ᑕᒪᓐᓇ ᐊᔾᔨᕐᓂᖅ. ᑭᓲᖏᑦ ᐱᑕᖃᖅᑐᑦ ᐅᑯᐊ ᓯᕗᓪᓕᕐᐹᑦ ᐱᓕᕆᔭᐅᔪᑦ ᑕᒪᑐᒧᖓ ᑕᖁᔭᐅᓯᒪᔪᓂᑦ ᑲᔪᓯᑦᑎᐊᖅᓯᒪᔪᑦ ᓯᕗᓪᓕᕐᓂ ᐊᕐᕌᒍᓂ ᑎᓴᒪᓂ (ᓱᕐᕌᓂᖓ 1) ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓐᓂᐊᖃᑎᒌᑦ. ᖁᔭᓐᓇᒦᒃ ᑕᒪᑦᓯ ᑐᑭᓯᓇᓱᐊᖃᑎᒌᑦ ᖃᐅᔨᓴᖅᑎᑦ, ᐃᓕᓐᓂᐊᖅᑐᑦ, ᐊᓯᖏᓪᓗ ᖃᐅᔨᓴᖅᑎᑦ, ᓴᓇᖃᑎᒋᔭᕗᑦ ᐊᒻᒪ ᐱᓇᓱᐊᖅᑎᕆᔭᕗᑦ ᐃᑲᔪᖅᑐᑦ ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓐᓂᐊᖃᑎᒌᒃᑯᓄᑦ ᑲᔪᓯᑦᑎᐊᖅᑎᓪᓗᒋᑦ, ᐊᒻᒪ ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓐᓂᐊᖃᑎᒌᑦ ᑭᓲᓂᖏᓐᓂᒃ ᑎᑎᕋᖅᑎᖏᑦ ᐱᓇᓱᐊᖃᑎᒌᓚᐅᖅᑐᑦ ᐅᓇ ᑎᑎᕋᖅᓯᒪᔪᖅ ᐱᔭᕇᑦᑎᐊᕋᓱᓪᓗᒍ.

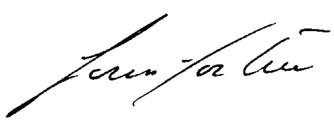
ᐃᓕᓴᐃᔨᒻᒪᕆᒃ ᓘᐃ ᑯᐊᑦᓯᔭᐃ, ᖃᐅᔨᓴᕐᓂᕐᒥᒃ ᑐᑭᒧᐊᒃᑎᑦᓯᔨ ᐅᑭᐅᖅᑕᖅᑐᕐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᒃᑯᓐᓂᑦ



AVANT-PROPOS

De toutes les régions du globe, c'est l'Arctique qui subit le plus sévèrement les impacts du réchauffement actuel de la basse atmosphère de notre planète. Déjà, plusieurs des symptômes d'un réchauffement arctique anticipés par les modèles climatiques sont confirmés par les observations en mer, sur terre et par satellite. Telles que résumées par le Arctic Climate Impact Assessment (ACIA 2004), les multiples perturbations environnementales, socio-économiques et géopolitiques affectant le monde arctique interagissent pour aboutir à une transformation irréversible du Nord. ArcticNet est un Réseau de centres d'excellence appuyé par les trois Conseils de recherche qui vise à aider le Canada à se préparer aux impacts de cette transformation. L'objectif central du Réseau est de générer le savoir et les analyses nécessaires à la formulation de stratégies d'adaptation et de politiques qui aideront les sociétés du Nord et de l'industrie à se préparer aux impacts de la transformation environnementale, économique et sociale et de la modernisation de l'Arctique canadien côtier. Notre vision est celle d'un futur dans lequel l'échange bilatéral de connaissances, la formation de la relève, le suivi et la modélisation de l'environnement permettent aux chercheurs et aux habitants du Nord d'atténuer les impacts négatifs et de maximiser les retombées positives de ces changements. Ce compendium présente les progrès effectués au cours de la deuxième année (2016-2017) des projets de recherche de la phase IV d'ArcticNet (2015-2018). Nous remercions tous les chercheurs principaux, étudiants, autres chercheurs, collègues et partenaires d'ArcticNet pour leur contribution aux nombreux et rapides succès du Réseau, de même que l'équipe éditoriale de ce compendium pour en avoir assuré la réalisation.

Louis Fortier, directeur scientifique d'ArcticNet



INTRODUCTION

ArcticNet Compendium Editorial Team

Mickaël Lemay, Ashley Gaden, Carl Barrette

This Compendium of Research (2016-17) presents research progress of the second year of Phase IV ArcticNet projects, which ran from 1 April 2016 to 31 March 2017. Forty-one projects were organized under five complementary research themes of Phase IV: 1) Marine systems (15 projects); 2) Terrestrial systems (10 projects); 3) Inuit health, education and adaptation (9 projects); 4) Northern policy and development (3 projects); and 5) Knowledge transfer (4 projects).

The preparation of this Compendium was aided by many people and organizations. We especially would like to thank Christine Demers, Claude Lévesque and all ArcticNet researchers and research partners for their valuable contributions to this document.

2016-2017

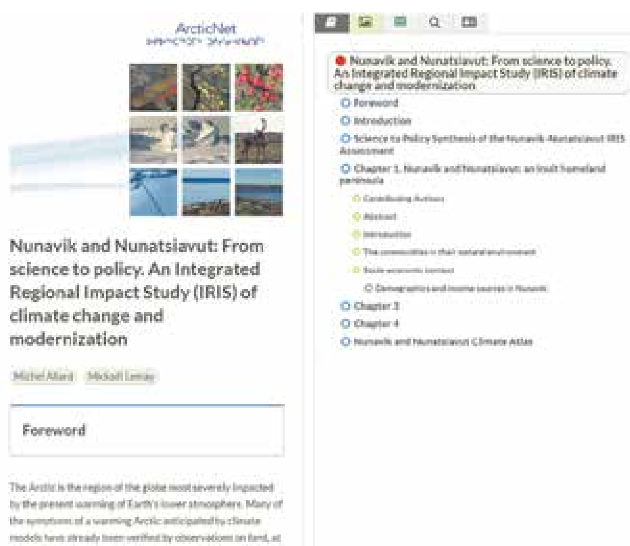
In the midst of its final phase of NCE funding, we are looking back over its tremendous accomplishments of the Network in fulfilling its central objective, namely, to study the impacts of climate change and modernization in the coastal Canadian Arctic and how these are being leveraged in ArcticNet's final three years.

ArcticNet has built 16 new partnerships during the last Phase of its NCE Program, including significantly increasing contributions from philanthropic sources. In this phase, a new ArcticNet-Parks Canada collaboration was established and funded by the W. Garfield Weston Foundation to describe the pelagic and benthic ecosystems of the Kitikmeot marine region where Franklin's ships *Terror* and *Erebus* were recently discovered. Subsequently, this $200,000 contribution from the Weston Foundation was increased $5.6 million to support a Greenland Circumnavigation Expedition. This Canada-Switzerland-Denmark-Russia collaboration will provide a unique opportunity to study some of the least accessible areas of the marine Arctic that are also key components of the system that regulates Earth's climate

The Network is seeing the fruition of its efforts to disseminate knowledge to decision-makers through its Integrated Regional Impact Studies (IRIS) and is now transforming this process to increase its relevance through the creation of a dynamic, knowledge-sharing IRIS Portal platform.

In 2016-2017 ArcticNet undertook a transformation of this process through the IRIS Portal project which will: (1) modernize the ArcticNet regional assessments to better address the needs of end-users for easily discoverable and accessible information; (2) develop a dynamic approach to provide results and recommendations in a timely fashion; and (3) evaluate the potential for the provision of specific science-based arctic assessments services, with the goal of becoming partially self-sustaining.

The capacity and momentum in Arctic research created by ArcticNet has stimulated the creation of large



ArcticNet IRIS Portal

academic "spin-off " programs such as the Hudson Bay System Study - BaySys Collaborative Research and Development project co-led by the University of Manitoba and Manitoba Hydro. Funded at a level of $15 million through an NSERC Collaborative Research and Development grant, this four-year program will improve understanding of the role of freshwater in the marine and coastal ecosystems of Hudson Bay allowing the differentiation of the impacts of climate change from hydroelectric regulation. Additionally, synergies created by ArcticNet led to the Université Laval-based program, Sentinelle Nord, a $98 million CFREF built around a transdisciplinary strategic framework consisting of key Research Chairs and Science Teams in each of its four Science Themes: Understanding the Complex Systems of Northern Environments; Impacts of Light in the North; Role of Microbiomes within Northern Ecosystems (Human and Natural); and, New Technologies for Northern Monitoring and Sustainable Development. The overarching goal of this cutting-edge 7-year program is to develop innovative new technologies and improve our understanding of the northern environment and its impact on human health.

Exemplifying the long-term value in basic research investments, ArcticNet saw a profound impact on policy-making this year in the contribution of ArcticNet-funded science to the Newfoundland and Labrador government's decisions during the Muskrat Falls controversy. In 2012, ArcticNet funded "Lake Melville: Our Environment, Our Health", a project to establish baseline ecosystem conditions to enable monitoring the impacts of industrial activity on Arctic estuaries and coastal Inuit communities prior to hydroelectric development. Fast forward to October 2016, when the research results unequivocally demonstrated that the flooding plan would result in methylmercury contamination of the watershed (http://www.cbc.ca/news/technology/muskrat-falls-labrador-mehylmercury-1.3821827). This work prompted Newfoundland and Labrador Premier Dwight Ball, in the midst of the Muskrat Falls project protest controversy, to revise the government's stance and commit to making all future decisions "using a science-based approach" creating a Committee of scientists to explore ways to reduce methylmercury contamination.

As these contributions to excellence in Canada's "science ecosystem" culminate, to highlight only a few is a challenge!

Louis Fortier
Scientific Director

Leah Braithwaite
Executive Director

SECTION I. MARINE SYSTEMS

Section I is composed of 15 ArcticNet research projects covering several biological, ecological, biogeochemical, and physical components of the Canadian Arctic marine systems.

HIDDEN BIODIVERSITY AND VULNERABILITY OF HARD-BOTTOM AND SURROUNDING ENVIRONMENTS IN THE CANADIAN ARCTIC

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ABSTRACT

Polar ecosystems are experiencing major stresses resulting from natural and anthropogenic causes and we need todocument the vulnerability of biodiversity and ecosystem functioning to changes that are already underway. Potential impacts of these stressors on benthic ecosystems in the Arctic are, however, still difficult to assess because of the lack of baseline data and incomplete sampling. For instance, hard-bottom and surrounding environments below SCUBA diving depths represent some of the most seriously undersampled habitats due lack of appropriate sampling gear. This is unfortunate since hard substrate habitats typically host a distinct fauna of sessile and movile invertebrates, and of fishes, some of which are highly vulnerable to damage from bottom-contact fishing gear. The advent of remotely operated vehicles (ROVs) offers now an excellent means of conducting *in situ* observations and samplings in these habitats. The research proposed here aims therefore at bridging this gap by investigating biodiversity, from microbes to fishes, and ecosystem functioning in the steep-and-deep and other previously unsamplable marine habitats of the Canadian Arctic. The objectives of this project are to: i) describe the biodiversity and functional role and the level of uniqueness of inaccessible habitats of hard-bottom seafloors including coral and sponge areas; ii) describe cryptic and microbial diversity associated with biogenic habitat-forming species; iii) compare microbial communities from RNA and DNA, to link communities' with biogeochemical processes and symbiotic relationships; iv) investigate the influence of cold-water corals on the diversity and composition of meiofauna/megafauna living in the surrounding soft-bottom sediments; v) identify environmental drivers of biotic communities in hard bottom habitats, including associated fish species, and; vi) explore if Arctic cod adopt a demersal distribution hugging the seafloor in July during maximum irradiance and minimum ice cover. All these objectives will be achieved with a SuperMohawk (SuMo) ROV based sampling. This project will also fund a major expansion of SuMo sample collection capabilities, and will elevate the profile of scientific ROV operations associated with the ArcticNet and CCGS *Amundsen*. Overall, this research program will bring new knowledge about the role of the biotic components of hard-bottom seafloors in the Arctic marine ecosystem, and will help our partners to establish monitoring programs and conservation strategies to respond to the challenges of environmental change. It will also enable Canada to fill his obligation under United Nation General Assembly 61/105 to identify and protect sensitive habitats including cold-water corals and sponges, seamounts and hydrothermal vents.

KEY MESSAGES

- Participated in ArcticNet cruises (2016) in the Baffin Bay region and in the Archipelago region.
- Six successful deployments of the SuperMohawk ROV (SuMo) and dives for video transects and sample collection, and precise location of box core and piston core targets.
- Successfully collected sponges and deep-water coral to study associated organisms.
- Exposed a new team of benthic and ROV researchers to Arctic research.
- Characterized multiple habitats through video transects, especially habitat that could not be sampled otherwise than with a ROV.
- Participation in the ArcticNet Annual Scientific Meeting has been useful for sharing ideas, discussing future work directions, and increasing our general understanding of ecological processes in the Arctic.
- Participated in national and international conferences and workshops.

OBJECTIVES

The objectives of this project are to:

1. describe the biodiversity and functional role and the level of uniqueness of inaccessible habitats of hard-bottom seafloors including coral and sponge areas;
2. describe cryptic and microbial diversity associated with biogenic habitat-forming species;
3. compare microbial communities from RNA and DNA, to link communities' with biogeochemical processes and symbiotic relationships;
4. investigate the influence of cold-water corals on the diversity and composition of meiofauna/megafauna living in the surrounding soft-bottom sediments;
5. identify environmental drivers of biotic communities in hard bottom habitats, including associated fish species; and
6. explore if Arctic cod adopt a demersal distribution hugging the seafloor in July during maximum irradiance and minimum ice cover.

INTRODUCTION

Since the first Canadian Arctic Expedition (1913-1918), many studies have described Arctic habitats and established baseline knowledge to evaluate and highlight the importance of climate change. However, even with major marine research programs over the last two decades in the Canadian Arctic (e.g. NOW, CASES, CFL, ARCTICNET, etc.), which represents 10% of the coastline of the world, some habitats and areas remain almost undescribed (Archambault et al. 2010, Piepenburg et al. 2011). Of particular note, hard-bottom and surrounding environments below SCUBA diving depths represent some of the most seriously undersampled habitats. Hard-bottom environments such as deep fjord walls, bedrock outcrops, and glacial tills in water provide habitat for a diverse polar ocean fauna (Dayton et al. 1995). Hard-bottom faunal assemblages in polar waters differ markedly from those on adjacent bottoms; traditional oceanographic gear such as grab samplers, box cores, multi-corers, and scientific trawls sample sediments much more effectively. These generally undersampled hard substrate habitats typically host a distinct fauna of sessile and vagile invertebrates, and of nektobenthic fishes (e.g. Copeland et al. 2012, Baker et al. 2012a,b, Roy et al. 2014). Hard-bottom environments are particularly common on steeply sloping bottoms, to the extent that habitat modelling efforts often use slope as a proxy for (hard) substrate (e.g. Bryan and Metaxas 2007). Some of the fauna of these steep-and-deep environments such as cold-water corals and sponges provide habitat for other invertebrates and fishes (Costello et al. 2005, Du Preez and Tunnicliffe 2011, Baillon et al. 2012), can be very long lived (Roark et al. 2005, Sherwood and Edinger 2009), and are highly vulnerable to damage from bottom-contact fishing gear (Hall-Spencer et al. 2002, Edinger et al. 2007, Roberts et al. 2009). They are therefore of particular concern for conservation. Cold-water corals in Canadian Arctic waters are the focus of a 2014-2017 DFO-funded research program aboard the CCGS *Amundsen* (Gilkinson et al. 2014) complementary to the current proposal. The research proposed here will investigate other elements of biodiversity in the steep-and-deep and other previously unsamplable marine habitats of the Canadian Arctic, from microbes to fishes. In particular, this ArcticNet project, HiBio, will bring together marine biologists and geologists from across Canada to study the microbial, invertebrate, and vertebrate biotas of hard-bottom environments of the Canadian Arctic. We will assess the previously hidden biodiversity of these hard-bottom environments, examining the extent to which they host previously unrecorded biodiversity, characterizing the faunal assemblages, and comparing the environmental drivers affecting hard-bottom species assemblages with those previously described for the Canadian Arctic, based mostly on samples from soft-bottom environments. Even with previous samples of soft-bottom environments, we still know little about how structurally complex hard substrate environments influence biodiversity in surrounding soft-bottom sediments that we identified during 2013 on the CCGS *Amundsen*. We hypothesize that oases of cold-water corals can enhance and diversify food available to surrounding environments, and may thus influence diversity and composition of nearby soft-bottom invertebrates. Given their life cycles and high turnover rates, meiofaunal assemblages are particularly sensitive to differences in food availability. This susceptibility is especially true for deep-water meio/megafauna which are more food- than space-limited. In general, the number of species depending on or associated with these reefs, and their full ecological importance/value, remains unknown.

Diversity of cold-water corals is thought to decrease northward and westward into the Arctic (Kenchington et al. 2010, 2011). Bycatch records indicate relatively high diversity of sea pens and soft corals, relatively low diversity of gorgonians, and unresolved diversity of black corals in Baffin Bay (Kenchington et al. 2010), with these estimates largely matched by *in situ* observations of corals during 2013-2016 *Amundsen* ROV expeditions (Neves et al. 2014, Neves et al. ASM 2014 talk, Edinger et al. 6th Deep-Sea Coral Symposium talk). Sponge bycatch has been quantified, but sponge diversity remains poorly known, because of limited targeted sampling efforts, lack of readily available ID guides, and minimal attention from taxonomists (Kenchington et al. 2010). Initial sampling in 2014-16 recorded several first records of sponge species in Baffin Bay previously known from boreal waters elsewhere in the North Atlantic and South Atlantic.

The sponge component of this project maps the abundance and diversity of demosponges and hexactinellid glass sponges in the Canadian Arctic, collecting enough physical samples to provide positive identification through spicule analysis. Furthermore, we will investigate sponge-associated biodiversity and functioning in all size classes (microbiota to megafauna), and estimate sponge food consumption and dissolved silica uptake.

Canada has an obligation under United Nation General Assembly 61/105 to identify and protect sensitive habitats including cold-water corals and sponges, seamounts and hydrothermal vents. Knowing the extent of previously hidden biodiversity found in steep-and-deep habitats will help Canada meet its obligations under this resolution. This resolution is very important especially in the Arctic regions. Numerous threats include commercial bottom trawling, cable and pipeline placement, bioprospecting and scientific sampling, waste disposal and dumping and ocean acidification. Oil and gas exploration, exploitation and decommissioning add additional threats to these vulnerable habitats. For decades, fishers trawling along the continental slope in the eastern and western North American coasts, have pulled up large pieces of coral entangled in their nets. Only recently, however, have scientists begun to study the impacts of fishing on cold-water corals.

The geological features that host hard-bottom faunas in the boreal regions of Atlantic Canada, such as moraines, till tongues and trough-mouth fans, and eroded bedrock features (Edinger et al. 2011) all occur within Baffin Bay and other parts of the eastern Canadian Arctic (Piper 2005). New data from the Geological Survey of Canada indicate fault scarps and mass transport deposits along the western slope of Baffin Bay (Campbell, GSC, unpubl., Edinger et al. 2015, GAC/AGU), and large active trough-mouth fans similar to the Disko fan that underlie the narwhal-coral closure (Neves et al. 2014) occur along the eastern side of Baffin Bay, mostly in Greenland waters. In addition, hard-substrate habitats are known to occur along fjord walls in Admiralty Inlet, Jones Sound, and Lancaster Sound but have never been sampled below 100 m depth. Given that the deeper and warmer Atlantic-derived water mass supports higher biodiversity in the Canadian Arctic Archipelago than the shallower and colder Pacific-derived water mass (Roy et al. 2014), the sampling of deep habitats becomes imperative for documenting hidden diversity in the Canadian Arctic.

Acoustic data of fish distribution and abundance validated by trawls have been accumulated since 2003.

Our recent synthesis of this information indicates that Arctic cod (*Boreogadus saida*) is by far (95%) the dominant pelagic fish in the Canadian Arctic (Fortier pers com). Starting in January, Arctic cod distribute over progressively deeper grounds as light and their vulnerability to surface-dwelling predators (seals, seabirds) increase over the winter. In July when light is at a maximum and ice is at a minimum, Arctic cod disappear from the water column, suggesting a demersal distribution that hides the fish from sonar detection. The ROV will enable us to test this hypothesis by direct observation of fish distributions immediately above and on the bottom.

Experimental fisheries provide another opportunity to sample previously unexplored biodiversity, and to simultaneously assess potential impacts of anticipated expanded fisheries on Arctic biodiversity and sensitive habitats. For example, experimental fishery expeditions for Greenland Halibut in Jones Sound in 2014-2016 were provided with coral and sponge identification guides and sampling kits and recovered high bycatch of the deep-water sea pen *Umbellula encrinus*, with inviduals as tall as 2.2 m (Neves et al. ASM 2014 poster). Other fauna recovered included carnivorous sponges, probably *Chondrocladia* sp. Through similar cooperative sampling efforts associated with other experimental fisheries throughout the Canadian Arctic, we will enable biodiversity surveys. Furthermore, our work can help to fill fundamental knowledge gaps on the unique geology and biological habitat of the shelf edge and continental slope of the Beaufort Sea where active hydrocarbon exploration will occur over the next decade. Recent surveys by the Geological Survey of Canada suggest that the unique bottom types in this environment will require sampling with a remotely operated vehicle (ROV) because features such as cold-seep-associated authigenic carbonates and mud volcanos could not be sampled with conventional sampling gear such an Usnel box corer or a small beam trawl (e.g. Foucher et al. 2010). The SuMo ROV associated with the *Amundsen* becomes the perfect tool to study active fluid-venting at the seabed. The best, if not only, way to study these under-studied, remote, and fragile habitats of high ecological value, is through the use of ROV, to better understand their diversity and their ecosystem functioning (Link et al. 2013a).

ACTIVITIES

1. Dissemination of scientific results

- Dissemination of results to the scientific communities, public, partners and stakeholders through high-ranking articles, either submitted (1), accepted or published (2).
- Dissemination of scientific results via oral presentations (5) and poster presentations (5) during national/international conference: ArcticNet Scientific Annual Meeting, Québec-Océan Annual General Meeting, 6th International Symposium on Deep-Sea Corals (Boston), and the 4th International Marine Conservation Conference (St. John's).
- Joli, Onda, Thaler, Carrier, Lovejoy and collaborators gave multiple presentations at the International Society for Microbial Ecology (ISME) Congres, held in Montreal. This was the largest, most prestigious conference on microbial ecology held over the last two years.
- A poster presentation of sponges collected in 2015 was presented at the 3rd International Workshop on Taxonomy of Atlanto-Mediterranean Deep Sea Sponges in Gijon, Spain in June 2016.
- An oral presentation of further results is being presented at the University of Alberta RE Peter Biology Conference in January 2017.

2. HQP training

- New PhD student started in June 2016 (Marie Pierrejean, June 2016).
- One PhD student completed her dissertation and graduated (B. de Moura Neves).
- New PDF started in October 2016 (B. de Moura Neves).

3. Field work in the Canadian Arctic

- Joint ArcticNet cruise on the CCGS *Amundsen* (Evan Edinger, Barbara Neves, Vonda Wareham, Sam Davin, Owen Sherwood, Curtis Dinn, Rachelle Dove, Christian Nozais, Marie Pierrejean, Mary Thaler). Co-funded by NSERC ship-time award ($270,000) to Edinger et al.
- Nozais was chief scientist during Leg 2a (14 July to 27 July 2016) onboard the *Amundsen*.
- Water column samples were collected at all HiBio stations.
- Successful sampling of over 50 specimens of thyasirid bivalves, including from a cold seep site on Northern Saglek Bank.
- Five locations in the Northern Labrador Sea and Baffin Bay were surveyed using the SuMo ROV during the CCGS *Amundsen* 2016 expedition. Four of these sites were in the northern Labrador Sea (NE Hatton Basin shelf, NE Hatton Basin outer slope, NE Saglek Bank, SE Baffin slope sponge hotspot), while additional ROV dives in the Disko Fan site in southern Labrador completed detailed video surveys, and facilitated precisely located box-coring and piston-coring to assess ecosystem function within bamboo coral forests, and to determine the initial age and accretion rate of the bamboo coral forest.
- Collection of water samples, plankton samples, in all ROV dive locations to characterize suspended organic matter concentration, quality, and stable isotopic composition, calcium carbonate saturation (dissolved inorganic carbon and total alkalinity), dissolved CO_2 and methane concentrations.
- Collection of box-core samples at all ROV dive stations to assess epifaunal and infaunal invertebrate macrofauna composition, and bottom types, and Agassiz trawl samples at some ROV dive locations to characterize epifaunal invertebrate biota.
- Multibeam surveys was conducted in the NE Hatton Basin (6 hours), SE Hatton Basin potential carbonate mounds site (6 hours), NE Saglek Bank Cold Seep (6 hours), NE Saglek Bank Coral hotspot (3 hours), SE Baffin Shelf sponge hotspot (4 hours) from where multibeam data was not previously available.
- Recovery of the Oceanlab Arctic camera lander from the vicinity of the Green Edge project ice camp.
- Sediment incubations have been done at one station to study biogeochemical nutrient fluxes at the interface sediment-water colum. These incubations will help to understand the functioning of the ecosystem in areas of hidden biodiversity.
- We also quantified seasonal variations in benthic faunal abundance and diversity and behaviour, at a high temporal resolution, using the Ocean Networks Canada seafloor cabled observatory located at 6-meter of water depth, in Cambridge Bay, Nunavut. Faunal composition and abundance were determined using an underwater HD video camera mounted on the instrument platform. The camera acquired 5-minute videos of the seabed at 2-hour intervals for more than two years. The image analyses performed are similar to the ones needed to analyse lander operation at station 177 and ROV HD video described earlier.
- Planning meetings and preparation for the ArcticNet cruises in 2017.

4. Field work in the context of international collaborations

- Invited participation to the Antarctica Circumnavigation Expedition onboard the *A. Tryoshnikov* (January & February 2017) to study changes that occurred following the 2010 calving in the Mertz glacier region, East Antarctica (P. Archambault).

5. Laboratory work, instrumentation, analysis

- We now have access to a sorting flow cytometer, which will enable us to select populations of cells for further taxonomic analysis.

- Metagenomic analysis of carnivorous sponge microbiomes (*Chondrocladia* and *Cladorhiza*) completed, and manuscript in preparation.
- Preliminary morphological analysis of thyasirid bivalves conducted (shell shape, internal anatomy, gill structure.
- Samples from the 2016 expedition are analyzed in several laboratories across Canada and these analyses are underway.
- Video analysis from 2016 expedition is underway.

6. Other activities

- In May 2016, R. Dove and S. Dufour visited scientists at the Canadian Museum of Nature, who provided us with access to previously collected specimens from the Canadian Arctic and shared their expertise. We will be sharing our results with them to help revise knowledge on molluscan diversity in the Arctic.

RESULTS

ROV dives and associated sampling on coral and sponge biodiversity hotspots

Six ROV dives were completed on five sites identified as possible biodiversity hotspots for corals and sponges in the Northern Labrador Sea and Southern Baffin Bay (Figure 1). Three of these sites were around the Hatton Basin – Eastern Hudson Strait coral and sponge hotspot, previously identified from coral and sponge bycatch data. Of these sites, highest coral biodiversity was observed at the NE Saglek Bank site, where several biogeographic range extensions were noted, including a unique NW Atlantic record of the lace coral, *Stylaster*, sp., and furthest north Canadian records of the white gorgonian coral, probably *Paragorgia johnsoni*, and the small soft coral *Clavularia* sp.

Two dives on opposite sites of the continental shelf break at the Hatton Basin (sites 1, 5) found a sponge-rich environment on the inner (shelf) side of the shelf-break, with a coral-rich biota on the outer (slope) side of the shelf break, although the sites were separated by less than 30 km. This coral-rich site was identified from fisheries observer bycatch data, and was dominated by the large, long-lived gorgonian coral *Primnoa resedaeformis*, much like the NE Saglek Bank site. The NE Saglek Bank site lies at the edge of the footprint of intensive fishing, and outside the voluntary closure in the Hatton Basin/Saglek Bank area. The two Hatton Basin sites are within the voluntary closure, and have received relatively little impact from fishing.

The sponge biodiversity hotspot on the SE Baffin shelf had high abundances of several species of large sponges, and a diverse fauna of smaller sponges. This site showed clear evidence of fishing impacts, particularly from bottom trawling, despite the fact that the precise positioning of ROV dive transect was chosen using fishing intensity data, to find areas that had not yet been trawled.

The final set of dives, at the Disko Fan bamboo coral forest site in southern Baffin Bay, completed additional video transects at a site first visited in 2013 (Neves et al. 2014), and allowed for extensive sample collection and precise placement of box cores and piston cores. Box core placement allowed comparison of ecosystem function measurements between the bamboo coral forest and adjacent areas from which the corals had been removed by trawling in 1999.

Dive 50: NE Hatton Basin (Site ROV1, 61°20.4921N, -61°9.4292W), July 18, 2016

At this site, ~1.1 km was surveyed. The surveyed line depth ranged between 562-573.5 m. Contrary to the indications of the pre-existing coral and sponge bycatch data, this site was sponge dominated, with very few of the heavily calcified corals that had been identified in trawl bycatch (Figure 2). Sponges were the most commonly observed organisms at this site, with glass sponge (possible *Asconoma foliate*)

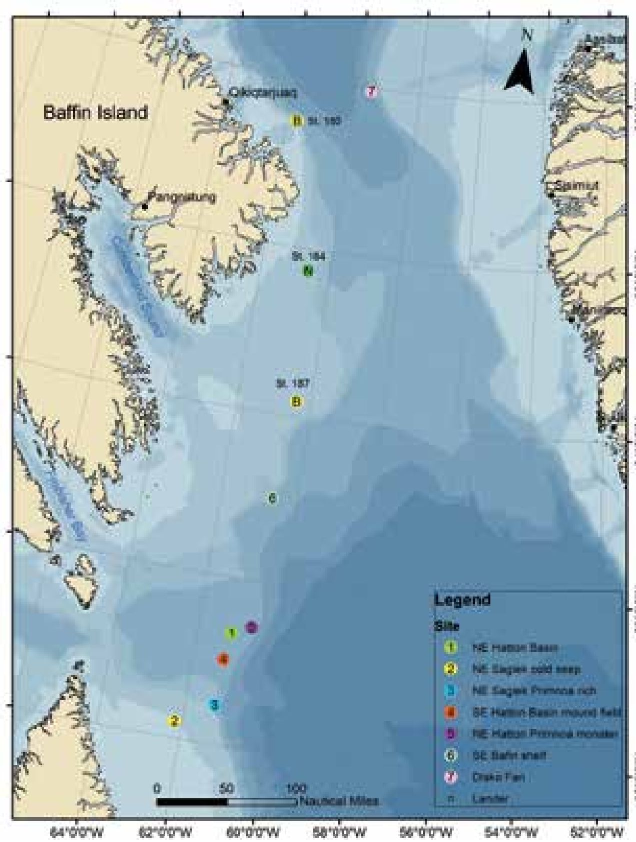

Figure 1. ROV dive locations visited during the 2016 CCGS Amundsen expedition. Order: 1, 4, 5, 2, 3, 6, 7. Note that dives were not carried out at sites 4 and 2.

and large *Geodia* sponges being the most abundant taxa observed during the dive. Other sponge species observed include *Polymastia* sp., *Phakellia* sp., *Mycale* sp., blue encrusting sponge, and *Geodia* with a yellow encrusting sponge (possible *Hexadella* sp.). Several species of corals were also observed, including soft corals (*Nephtheids*, and *Anthomastus* sp.), sea pens (*Halipteris* sp.), and one observation of *Acanthogorgia armata*. Sea anemones, a deep-sea crab, and squat lobsters were also seen near the bottom during the dive. Amphipods, adults with red bodies and juveniles with black bodies, were also very conspicuous at this site swimming in the water column and often swarming the ROV during transect. A few specimens of this amphipod were sampled with the sampling skid. Fish such as redfish (Family Trachichthyidae), grenadier (Family Macrouridae) and skate (Rajidae) were also observed. No *Primnoa resedaeformis* large gorgonian corals were observed, contrary to the indications from the Northern Shrimp Survey bycatch data. In terms of bottom type, the surveyed site was mainly sandy cobbly gravel, with occasional boulders. Many of the larger sponges, and all of the larger corals, were attached to the boulders. The multibeam survey and sub-bottom profile indicated an iceberg-scoured acoustically incoherent generally flat bottom, with undulating topography on the scale of 5 m.

Site ROV4: SE Hatton Basin carbonate mounds. No ROV dive or direct sampling: multibeam and sub-bottom survey only, July 18, 2016

Following the ROV dive at station ROV1, the ROV pilots informed us that repairs to the ROV would require long delays, with a possible missed diving day. We carried out a multibeam sonar and sub-bottom profile survey of the reported mound field at station ROV 4, about 15 nautical miles to the south of station ROV1. A mound field, possibly composed of authigenic carbonates or other hydrocarbon seep materials had been reported in this location (Jauer and Budkewitsch 2010). The multibeam and sub-bottom profile surveys showed extensively ice-scoured relatively flat bottom, acoustically incoherent, with undulating topography, generally similar to the bottom type at station ROV1. No evidence for an authigenic carbonate mound field was observed in multibeam. The sub-bottom profile indicated one small region where a possible, somewhat indistinct, unconformity may have separated undulating topography up to 10 m high from a relatively flat acoustically incoherent bottom below, consistent with the acoustic characteristics of hydrocarbon-seep related mounds.

Dive 51: NE Hatton Basin Mercers Monster (Site ROV5, 61°26.4154N, -60°39.8628W), July 19, 2016

Site ROV5 is based upon extensive bycatch of the large gorgonian coral *Primnoa resedaeformis* in a commercial fisheries trawl in May 2007, a few weeks

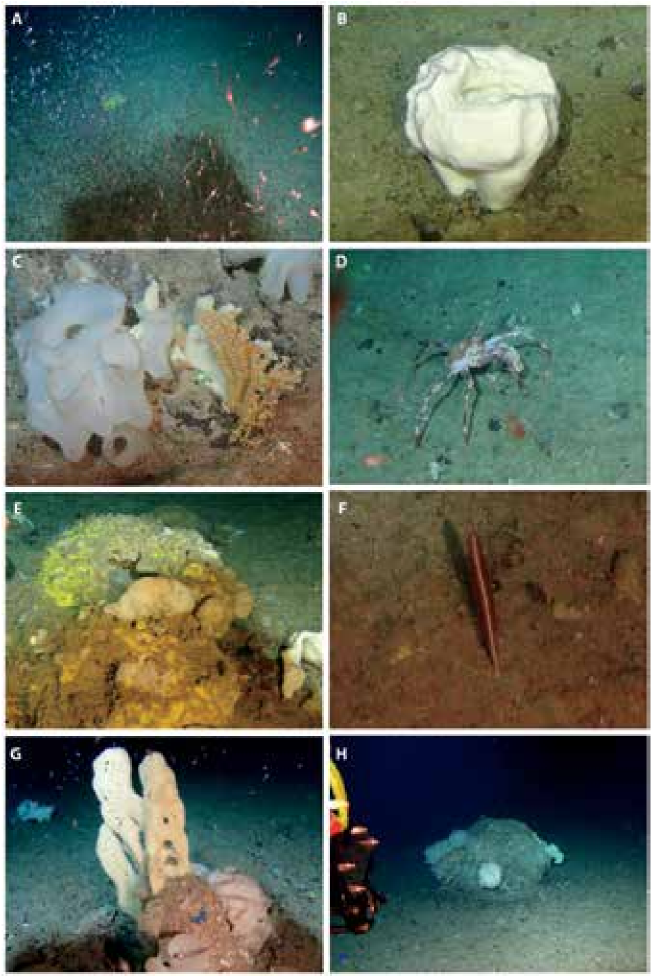

Figure 2. Photo-plate of megafauna observed during the ROV video transect at site 1 (NE Hatton Basin): A) abundant amphipods in the water column, B) Geodia sp., C) Asconema sp. sponge, Acanthogorgia sp. yellow coral, D) Large unidentified crab, E) Geodia sp., Polymastia sp., yellow encrusting sponge, F) Sea pen (Halipteris sp.), G) Mycale sp., H) Boulder with Asconema sp., Geodia sp., and other sponges.

after three fishing industry groups announced a voluntary fisheries closure in the Hatton Basin region. Multibeam sonar of this region had been collected in 2006. Because the commercial trawl path was 16 km in length, a 3.5 kHz sub-bottom profile line was recorded along the length of the trawl path, in order to determine the regions with hard bottoms, the preferred bottom types of *Primnoa resedaeformis*. The sub-bottom profile identified the portion of the trawl path closest to our originally planned ROV transect as a hard-bottom region.

At this site, repairs to the ROV following the previous dive delayed the dive and bottom time was limited to 1 hour, due to the loss of hydraulic pressure. We prioritized sampling over a video transect, and therefore we stayed in the vicinities of the site where the ROV landed, as it was suitable for sampling. A total of 10 samples of corals and sponges were collected at this site, along 158 m of surveyed bottom. The surveyed depths ranged between 626-633 m. Because the ROV had to be recovered so early into the dive, we did not reach the trawl path, and we were unable to directly measure the impact of this commercial fisheries trawl on the *Primnoa* corals at this site. Large gorgonian corals (*Primnoa resedaeformis*) and soft corals (*Duva florida*) where conspicuous at this site (Figure 3). Other corals include one sea pen (*Pennatula* sp.), several sea mushroom corals (probably *Anthomastus* sp.), and nephtheid soft corals. Colonies of *D. florida* were very abundant on gravel and on boulders where *Primnoa* corals were found. Some *D. florida* colonies reach 16 cm in height, while *Primnoa* colonies reach 60 cm.

Sponges were also a significant component of the benthic fauna at this site, including *Geodia* spp., glass sponges (*Asconoma* cf. *foliate*), and large unidentified lobed sponges. Most taxa were observed attached to hard substrates including boulders, cobble, and dead fragments of *Primnoa*. Both live and dead *Primnoa* were collected, as well as sponges including a glass sponge, *Mycale* sp., and an unidentified species. Other observed megafauna include sea anemones, shrimp, sea stars, hydroids, and bryozoans. One live and several dead *Primnoa* where collected. The dead *Primnoa* samples are particularly valuable for paleoceanographic analysis, due to their skeletons made of both calcite and protein.

The bottom type was sandy gravel with cobbles and large boulders. The site surveyed was sloping gently toward the open Labrador Sea, rather than being the flat iceberg-scoured facies within the Hatton Basin. A longer dive in this region, as originally planned, would have allowed us to survey the three geomorphic facies represented here, including the deeper rill-and-gully zone, the gently sloping unscoured zone that we surveyed, and which was sampled by the trawler, and the flat iceberg-scoured zone at the top, and on the Hatton Basin side of the sill.

Site ROV2: NE Saglek Bank suspected cold seep (60°19.302N, - 62°12.408W), July 20, 2016

No ROV dive was completed at the site of the suspected cold seep, as the ROV required more than one full day's worth of repairs after the first two short dives. At this site, we completed a multibeam sonar and sub-bottom profile survey in an effort to locate the source of the oil slick observed at the surface in Radarsat imagery (Budkewitsch et al. 2014). Our hope was that if oil or methane gas were actively seeping from the seafloor, they would be visible in the multibeam sonar, and possibly also within the sub-bottom profile. We were also expecting to possibly find pockmarks on the surface if there was active gas venting. Neither the water column sonar nor the multibeam sonar and sub-bottom profiler revealed any direct evidence of the oil seeping from the bottom. Scientific crew on the deck during the collection of box-cores, however, did see oil sheen on the surface of the water.

Water sample collection at this site included two CTD and Rosette casts, which included water samples that will be analyzed for dissolved methane (Punshon et al. 2014). Plankton collected at this site may also show petroleum residues on analysis. Triplicate box cores were collected at this site. The box cores yielded muddy coarse sand sediment, that also included bryozoans, and more significantly, abundant thyasirid bivalves, which are hypothesized to host methanotrophic bacteria that feed upon the hydrocarbons emanating from the bottom.

En route to ROV site 3, we collected additional multibeam data, and two additional box cores, at a site identified from seismic data as possible cold seep mound (Jauer and Budkewitsch 2010; site ROV2b in the dive plan). Closer inspection in multibeam and sub-bottom profile, and box coring, revealed this

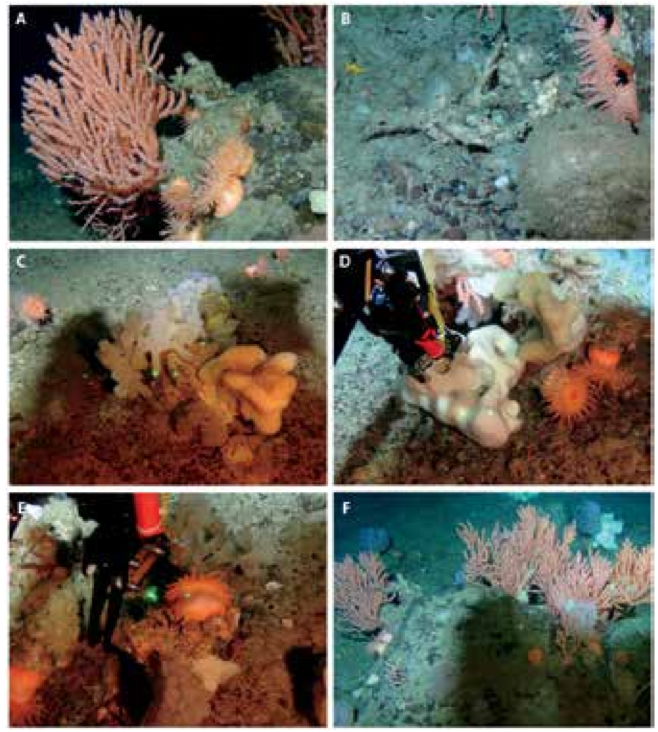

Figure 3. Photo-plate of megafauna observed during the ROV video transect at site 5 (NE Hatton Basin Primnoa monster): A) Boulder with Primnoa, sea anemones, soft corals, shrimp, sponges, dead Primnoa bases, B) Dead Primnoa base, hispid Geodia sp., sea anemones, C) Asconema sp., soft corals, other sponges, sea anemones, D) Geodia sp., Mycale sp., sea anemones, Primnoa, and dead Primnoa skeleton, E) Boulder with Primnoa, soft coral, sea anemones, dead and Primnoa bases.

possible mound to be a ridge composed of winnowed muddy sandy gravel, similar in composition to the winnowed ice-contact sediments seen at Station ROV2, and at station ROV1. We found no evidence of seabed structures produced by hydrocarbon seep-related authigenic carbonates in these locations.

Dive 52: NE Saglek Primnoa Rich (Site ROV3, 60°28.0348N, -61°16.687W), July 21, 2016

At this site, a 1 km transect was surveyed due to very strong currents that prevented the dive to carry on. The surveyed depths ranged between 461-473 m. Abundant amphipods and marine snow were noticed in the water column during this dive. This site was dominated by large densely encrusted boulders populated with corals (*Primnoa resedaeformis*, *Paragorgia arborea*, *Duva florida*), hydrozoans, bryozoans, sea anemones, and sponges (*Geodia* spp., *Asconema* cf. *foliate*, *Phakellia* sp., Figure 4). *Primnoa resedaeformis* colonies were large and frequently observed on boulders, and smaller (i.e. juvenile) colonies on cobble. Colonies of *Paragorgia* sp. where infrequent with only three small colonies noted. Some *P. resedaeformis* colonies had parasitic hydroids growing on them. Several colonies were tipped over, possibly due to a combination of heavy weight and strong currents; although the possibility of physical contact with fishing gear in this heavily fished area should not be discarded. Dead fragments of *P. resedaeformis* were also observed at this site, but much less than during the previous dive at NE Hatton Basin (site 5, dive 51). Colonies of the soft coral *Duva florida* were large and abundant, reaching up to 30 cm in height and often growing on cobbles and pebbles. Other soft corals species were noted (nephtheids, *Anthomastus* sp.) throughout the dive particularly on cobble and pebbles. One sea pen colony (*Anthoptilum grandiflorum*) was also observed. Many sponge species were also observed including *Geodia* spp., glass sponges (*Asconoma* cf. *foliata*), *Polymastia* spp., vase sponges (*Phakellia* sp.) and a large unidentified lobed sponge. Other invertebrates included echinoderms (mud stars), decapods (shrimp, squat lobster, crab), and sea anemones. Most taxa were observed attached to hard substrates including boulders, cobble and dead fragments of *Primnoa*. A live *Primnoa* colony was collected, along with two sponge species. Dead *Primnoa* at this site were considerably less common than in the small portion of the site ROV5 dive that was completed. Fish observed during this dive include grenadier (Family Macrouridae), Greenland cod (*Gadus ogac*), spotted wolfish (*Anarhichas minor*), redfish (Family Trachichthyidae), and a skate (Rajidae). Interestingly, the Atlantic cod individual was observed resting beneath a boulder, in a cavity very similar to those used by wolffish for denning.

Boulders were colonized by *Primnoa*, hydroids, bryozoans, sea anemones, and sponges (encrusting yellow sponge), with colonies to 1-1.5 m height common. In the region of the ROV transect through which the scientific survey trawl passed, many of the *Primnoa* corals were inclined about 15-25 degrees to the southeast, in the direction of the prevailing currents, but also in the direction that the trawl swept the bottom. No trawl door scars or other direct evidence of trawl damage was observed. Three small

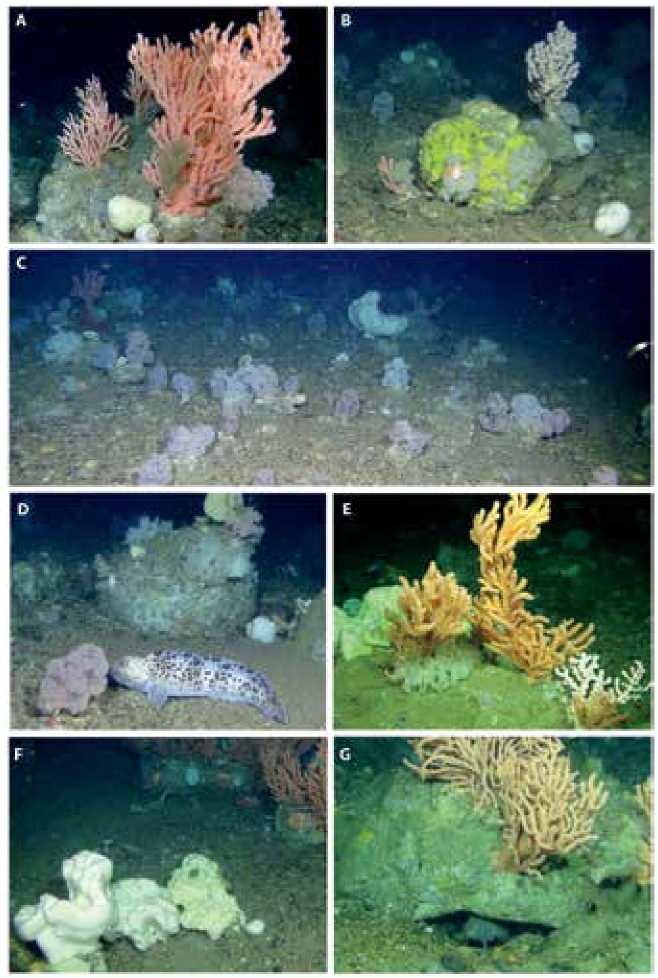

Figure 4. Photo-plate of megafauna observed during the ROV video transect at site 3 (Saglek Primnoa rich): A) Boulder with Primnoa, soft corals, hydroids, Geodia sp., and other sponges, B) Sponge or boulder encrusted with yellow sponge, small Primnoa sp., Paragorgia sp., C) Soft corals (likely Duva florida), Primnoa sp., Geodia sp., D) Northern Spotted Wolfish, soft corals and sponges, E) Boulder with Primnoa sp., Geodia sp., Asconema sp., Paragorgia sp.; F) Irregular Geodia sp. with varying colour morphs, G) Gadus sp. (cod) under boulder with Primnoa attached.

colonies of *Paragorgia arborea* where observed with the largest reaching 53 cm in height - adult colonies of this species can reach up to 3 m. High bycatch values of this species were observed in Northern Shrimp Survey trawls in shallower water close to this site, but were not recorded in the trawl that this ROV dive crossed. We also observed two colonies of white *Paragorgia* sp., which is much rarer than the red form of this gorgonian, and has not been recorded in the northwest Atlantic north of the Stone Fence, in Nova Scotia.

Dive 53: SE Baffin Shelf (Site ROV6, 62°59.181N, -60°37.7177W), July 22, 2016

At this site, the planned transect length was 2.8 km, but only ~260 m were surveyed due to problems with the ROV cage camera. The surveyed line depth ranged between 492-500 m. Sponges were the most commonly observed taxa throughout this dive, with *Asconema foliata*, *Polymastia* spp., and *Geodia* spp. being the most abundant species observed (Figure 5). In general, sponges were noticeable smaller throughout the dive with the exception of a few isolated colonies of *Geodia* spp. and of A. *foliate* – the latter was observed with juvenile basket stars (*Gorgonocephalus* sp.), hydrozoans, crinoids, and amphipods living in the oscula of this colony. In terms of corals, only small soft corals where observed (*Nephtheid* spp., *Anthomastus* sp.) along with one sea pen (*Pennatula* sp.), with no large gorgonian corals documented. Other observed taxa included hydrozoans, basket stars (*Gorgonocephalus* sp.), ceriantharians, and bivalves. Individual redfish (Family Trachichthyidae) where commonly seen throughout the dive, and a polar sculpin (*Cottunculus microps*). Evidence of recent fishing activities where observed including trawl door marks, fragments of *A. foliate* drifting across the sea floor, and numerous fishing boats noted in the vicinity on the ship's sonar.

Dive 54: Disko Fan 1 (Site ROV7, 67°58.1268N, -59°30.24W), July 24, 2016

Prior to arrival at this dive site, we collected two sub-bottom profiles at 4 km passing over the region to be surveyed using the ROV. These sub-bottom profiles showed small ridges of unstratified sediment superimposed on the Disko Fan, with small valleys containing stratified sediment between them. Ridges were mostly in the 5-10 m height range, with one ridge approximately 15 m in height approximately three nautical miles from the intended dive site. A second line measured perpendicular to slope, following one ridge, found, not surprisingly, an even slope of unstratified sediments. Visual observations on the bottom indicated that corals were more common on small topographic rises, raising the hypothesis that the corals had created the topographic rises by baffling sediment. During both ROV dives, we selected sites for piston coring with abundant corals in large patches that could be targeted by the piston core, and that co-incided with two ridges identified on the sub-bottom profile and multibeam sonar.

At this site, the planned transect length was 1.7 km, but only ~271 m were surveyed in search for appropriate locations for box-cores and piston cores. The surveyed line depth ranged between 924-941 m. Instead of starting the dive at waypoint 1 where sampling could not take place (DFO monitoring buffer zone), the ROV landed at waypoint 2, where dense colonies of *Keratoisis* sp. were readily observed. Colonies were seen forming dense patches in a muddy substrate, as observed in 2013 at a nearby location. Although live colonies were the most common form of this coral, fragments of dead colonies were also observed as we approached the trawl path from a DFO survey that occurred in 1999 in this area. There were no signs of recovery, as no colonies were observed in the area with dead colonies. A gillnet was also encountered near a coral patch, restating the exposure of these colonies to different types of fishing gear. Crinoids and sponges were commonly observed living on *Keratoisis* sp. colonies. Other observed invertebrates include sea pens (probably *Pennatula grandis* and *Anthoptilum grandiflorum*), sponges (e.g. *Asconema* sp., and unidentified taxa) sea stars (e.g. *Solaster* sp.), and yellow parasitic zoanthids overgrowing

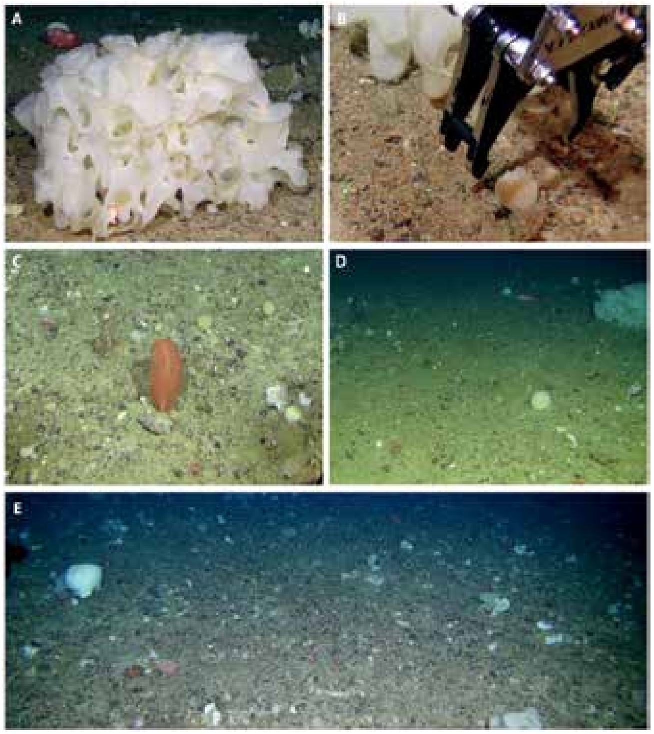

Figure 5. Photo-plate of megafauna observed during the ROV video transect at site 6 (SE Baffin shelf): A) Asconema sp., redfish, bryozoans, echinoderms, B) Sampling Polymastia sp., C) Sea pen (possibly Pennatula grandis), D) Polymastia sp., Asconema sp., redfish, E) Geodia sp., other sponges, gravelly bottom.

colonies of *Keratoisis* sp. Skates, Greenland halibut (*Reinhardtius hippoglossoides*), polar sculpin (*Cottunculus microps*), and rocklings (*Gaidropsarus* cf. *argentatus*) are among the fish observed during this dive (Figure 6). A total of four samples were collected during this dive, including live and dead *Keratoisis* sp, skeletons from a trawl path in order to look to for *Keratoisis* sp. recruits, the parasitic zoanthid, and sponges.

Dive 55: Disko Fan 2 (Site ROV7, 67°58.1244N, -59°30.27828W), July 25th 2016

We decided to start this dive at waypoint 2 and follow a transect towards the northeast, by crossing ridges identified in the sub-bottom profile and multibeam. The transect direction was adjusted during the dive, as the ship needed to deviate from ice. At this site, ~2 km of bottom were video-surveyed, across depths ranging between 874-934 m. As observed during dive 54, dense patches of *Keratoisis* sp. were identified during the transect, alternating with bare sediment areas where a few other invertebrates were observed (Figure 7). *Keratoisis* sp. forests were readily identifiable in the sonar. The overall megafaunal diversity seemed similar to the observed during dive 54 at a nearby location, with some differences. The sea pen *Umbellula* cf. encrinus, the bamboo coral Acanella arbuscula, and the solitary scleractinian *Flabellum* sp. were observed during this dive, but not during dive 54. Samples collected during this dive include both live and dead fragments of *Keratoisis* sp., as well as sponges. Similar with fish observed in both dives, with the exception of northern wolfish (*Anarhichas denticulatus*) documented during this dive.

The three piston cores from the Disko Fan site penetrated locations on small ridges, with two cores on one ridge, and the third core on a different ridge about 500 m distance (Table 1). It is possible that the ridges may have been made by accumulation of baffled sediments among corals, analogous to the growth of *Lophelia pertusa* cold-water coral reefs (e.g. Titschak et al. 2015).

Piston cores were returned to the Geological Survey of Canada (Atlantic) and X-rayed before sectioning. Of the three cores, only core 2016804014 penetrated buried bamboo coral thickets. Bamboo coral fragments were found to ~50 cm depth in the main core, and to 130 cm in the trigger-weight core, which typically loses less fine-grained material from the surface. The deepest coral fragments recovered in the cores were found immediately above the shallowest glaciomarine till tongue sediments (Figure 8), suggesting that the bamboo coral forest has been growing at this location for several thousand years, at least. Radiocarbon analysis of buried coral fragments within the piston cores, noting depth of fragments,

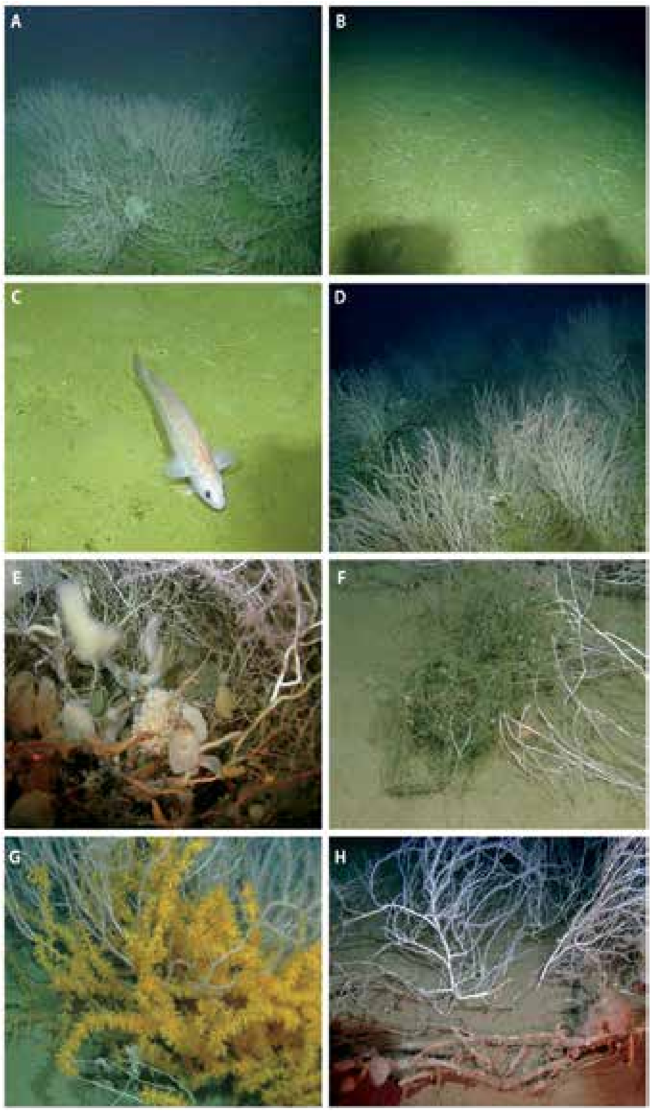

Figure 6. Photo-plate of megafauna observed during the ROV video transect at site 6 (SE Baffin shelf): A) Keratoisis colonies, B) Broken corals near the trawl path, C) Fish, D) Keratoisis sp. bush, E) Sponges on dead coral skeleton, F) Fishing line caught in corals, G) Parasitic zooanthid growing on Keatoisis sp., H) Dead coral skeleton with attached sponges.

will be used to assess sediment accumulation rates and, more significantly, the time span over which the *Keratoisis* coral forests have been growing.

Cryptic invertebrate biodiversity associated with bamboo corals (V. Wareham, B. Neves)

Dense patches, or forests, of *Keratoisis grayii* were surveyed during Remotely Operated Vehicle (ROV) operations at Disko Fan (SE Baffin Bay) during Leg 2a of the 2016 *Amundsen* expedition. At this site, fragments of *K. grayii* were collected using the ROV primarily for geochemical studies involving long-standing questions about nutrient availability and transport in the Labrador Sea and southern Baffin Bay. However, preliminary examination of the samples revealed a high biodiversity hidden within the branches of the coral forests. As a result, an opportunity for a secondary study emerged: 'Hidden biodiversity within deep-water bamboo coral forests in the Canadian Arctic".

Samples are now being processed for DNA barcode analysis, as an attempt to identify the species found in association with the coral.

Seasonal and interannual changes in ciliate and dinoflagellate species assemblages in the Arctic Ocean (Amundsen Gulf, Beaufort Sea, Canada) (D.F. Onda, E. Medrinal, A.M. Comeau, M.Thaler, M. Babin, C. Lovejoy)

Recent studies have focused on how climate change could drive changes in phytoplankton communities

Table 1. Piston Cores collected at Disko Fan bamboo coral forest site.

Core number	Latitude	Longitude	Depth (m)	Penetration (cm)
2016804014	67°58.152'N	59°30.171'W	913	201
2016804015	67°58.183'N	59°30.239'W	915	155
2016804016	67°58.073'N	59°29.390'W	874	128

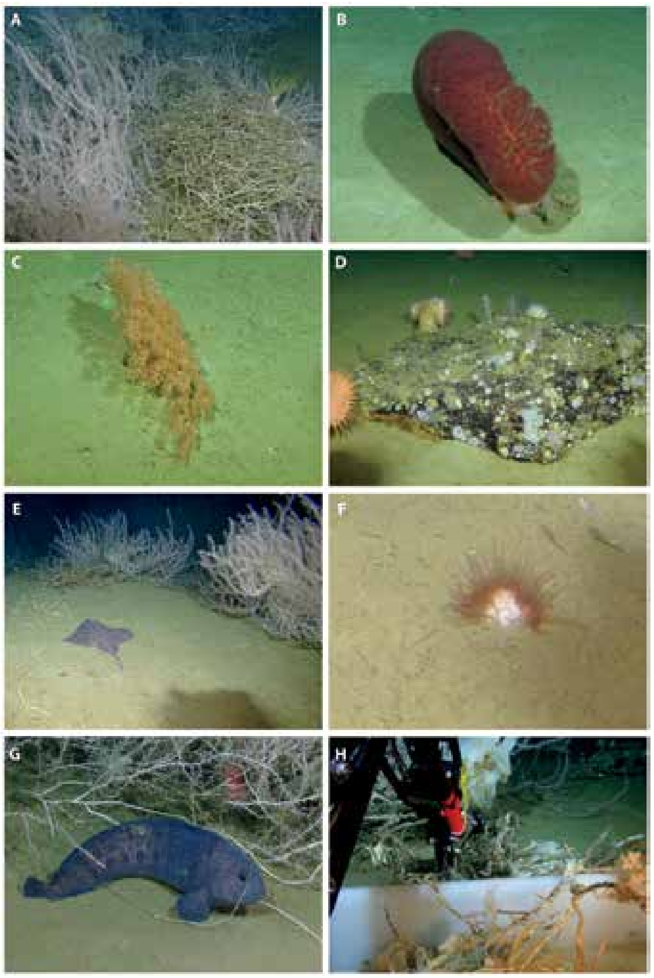

Figure 7. Photo-plate of megafauna observed during the ROV video transect at site 7 (Disko Fan, dive 55): A) Keratoisis sp., B) Sea pen (Anthoptillum grandiflorum), C) Acanthogorgia sp., D) Boulder with Polymastia sp., Asconema sp., soft corals, tunicates, sea anemones, E) Skate, broken coral pieces, live coral, F) Flabellum sp., G) Northern wolfish, H) Sampling dead coral encrusted with sponges.

in the Arctic. In contrast, ciliates and dinoflagellates that can contribute substantially to the mortality of phytoplankton have received less attention. Some dinoflagellate and ciliate species can also contribute to net photosynthesis, which suggests that species composition could reflect food web complexity. To identify potential seasonal and annual species occurrence patterns and to link species with environmental conditions, we first examined the

Figure 8. X-ray of trigger-weight core 2016804014 showing bamboo coral fragments immediately above glacial-age diamict, Disko Fan site, ~913 m water depth.

seasonal pattern of microzooplankton and then performed an in-depth analysis of interannual species variability. We used high-throughput amplicon sequencing to identify ciliates and dinoflagellates to the lowest taxonomic level using a curated Arctic 18S rRNA gene database. DNA- and RNA-derived reads were generated from samples collected from the Canadian Arctic from November 2007 to July 2008.

The proportion of ciliate reads increased in the surface towards summer, when salinity was lower and smaller phytoplankton prey were abundant, while chloroplastidic dinoflagellate species increased at the subsurface chlorophyll maxima (SCM), where inorganic nutrient concentrations were higher. Comparing communities collected in summer and fall from 2003-2010, and found that microzooplankton community composition change was associated with the record ice minimum in the summer of 2007. Specifically, reads from smaller predatory species like *Laboea*, *Monodinium* and *Strombidium* and several unclassified ciliates increased in the summer after 2007, while the other usually summer-dominant dinoflagellate taxa decreased.

Temporal and distributional studies of ciliates and dinoflagellates are usually restricted to morphologically recognizable taxa. The use of HTS coupled with the improved reference database provided higher resolution of potential species that suggests high diversity compared to previous reports from the Arctic. Season and depth the major factors that grouped ciliates and dinoflagellates using the network analyses. The seasonal changes in microbial composition suggested shifts in dominant function within the two groups (Figure 9). We found indicator species for the oligotrophic conditions that may dominate the future Arctic, these smaller microzooplankton taxa would have the ability to exploit smaller prey.

Bacterial community structure of carnivorous sponges (J. Verhoeven, S. Dufour)

Analysis shows that *Chondrocladia* houses bacterial communities with a higher diversity than those observed in *Cladorhiza*. High abundances of Flavobacteriaceae were observed within *Chondrocladia* and Cladorhiza. *Chondrocladia* bacterial communities contain additional families with fluctuating rates including the Rhodobacteraceae, Halieaceae, the "Sva0996 marine group" of *Acidimicrobiia*, Colwelliaceae and Hyphomonadaceae (Figure 10). Enrichment of specific bacterial genera was consistently seen amongst anatomical regions of *Chondrocladia*. These enrichments are suggestive of a functional role for these bacteria within host biology possibly including prey associated chitin digestion (*Colwellia* and *Reichenbachiella*) and sedimentary nutrient acquisition (*Robiginitomaculum*). In contrast, a less conserved microbiome, with more variation between sponge individuals was seen within *Cladorhiza*.

Our results highlight both the stability and versatility of the carnivorous sponge microbiome and shows the existence of diverse bacterial microcosms within *Chondrocladia* and *Cladorhiza*. The bacterial associations documented here could indicate a multi-faceted approach to nutrient acquisition within *Chondrocladia*, potentially utilizing carnivorous feeding and bacterial mediated breakdown of hydrocarbons in sediments. This work helps us understand the function of carnivorous sponges within arctic benthic ecosystems.

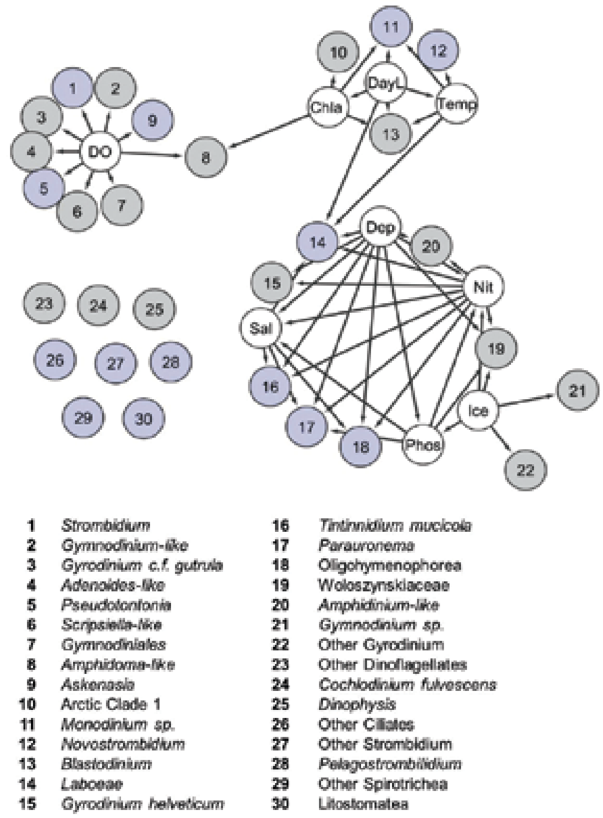

Figure 9. A network based on significant Spearman's rank correlation ($r = > 0.3$, $p < 0.001$) showing the strong association of different ciliates and dinoflagellates with environmental variables such as dissolved oxygen (DO), total chlorophyll a (chl a), daylength (DayL), temperature (Temp), depth (Dep), salinity (Sal), nitrate+nitrite (NO_3^-), phosphate (PO_4^{3-}) and ice. Blue circles correspond to ciliates and grey on dinoflagellates. Taxonomic identities of the numbers in the circles are presented below the network.

Regional fish biodiversity and associations with corals and sponges (B. Neves, K. Hedges, P. Snelgrove, E. Edinger)

The main objective of the fish biodiversity component of our project is to investigate the biodiversity and distribution of demersal ichthyofauna in Baffin Bay and Davis Strait, and to assess corals and sponges as potential fish habitat. Our dataset consists of (1) fish and invertebrates presence, abundance, and biomass data from Fisheries and Oceans Canada (DFO) fish stock assessment trawl surveys, and (2) high definition video data obtained using the Super Mohawk remotely operated vehicle (ROV) deployed from CCGS *Amundsen.*

The DFO database include data collected during trawl surveys that occurred between 2004 and 2015 in North of Labrador and Baffin Bay regions, at average depths ranging between 72 and 1490 m. Over 200 fish species were identified during the surveys, with additional 24 species of coral and 66 species of sponges. Preliminary analyses indicate that gear type, location, and depth influence fish biodiversity patterns in this region. Relationships between fish and coral-sponge biodiversity will therefore be assessed by controlling these variables.

Analysis of ROV video surveys (2013-2016) conducted in Baffin Bay and N Labrador so far indicates lower diversity and abundance of fish and coral species in the region of Baffin Bay in relation to the ROV surveys.

Fish species identified from the videos represent at least nine families, including Greenland halibut, grenadiers (Family Macrouridae), eelpouts (Lycodes sp.), skates (family Rajidae), redfish (*Sebastes* sp.), rocklings (*Gaidropsarus* sp.), wolffish (*Anarhichas minor* and *A. denticulatus*), Greenland cod (*Gadus ogac*), sea snails (e.g. *Careproctus reinhardti*), and sculpins. Corals from five families have been identified from ROV videos, including nephtheid soft corals, bamboo corals (*Keratoisis* sp.), and sea pens (*Umbellula encrinus*, *Anthoptilum grandiflorum*, and *Pennatula* sp.). Analysis is still ongoing to better assess fish biodiversity in the surveyed sites.

Regional sponge biodiversity (C. Dinn, S. Leys, V. Wareham)

During Leg 2A of the 2016 CCGS *Amundsen* expedition, sponges were collected from sites in the Northeast Atlantic – east of Baffin Island. Sponges were obtained through Box cores, Agassiz trawls, and though targeted sampling using the SuMO ROV. Sponges were photographed *in situ* using the ROV mounted camera and once on deck samples were photographed, cataloged and preserved frozen

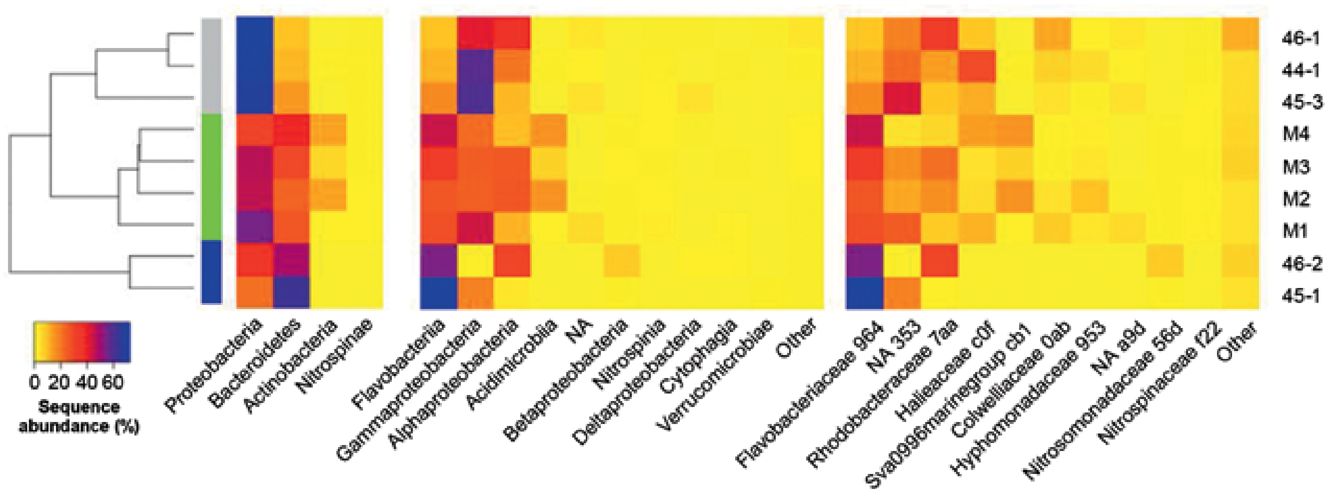

Figure 10. Bacterial community structure of the carnivorous sponges Chondrocladia sp. and Cladorhiza sp.. Shown are the most common phyla, families and orders. Squares indicate relative abundance of each taxa ranging from yellow (low, 0%) to blue (high). Bars indicate sample type, grey: Chondrocladia specimens from arctic regions, green: Chondrocladia specimens from the Gulf of Maine and blue: Cladorhiza specimens from arctic regions. The dendrogram displays the Jensen–Shannon divergence based hierarchical ward D2 clustering of bacterial communities.

for taxonomy. Subsamples of each specimen were preserved separately in 95% ethanol for DNA analysis using cytochrome oxidase subunit I (COI) mitochondrial DNA. In total, during this leg of the cruise, 112 separate specimens were collected at depths ranging from 80 to 1148 m at latitudes 60°18N to 68°15N. A total of 31 specimens were collected using the ROV with associated *in-situ* video imagery, which will aid in species identifications and descriptions.

The diversity of deep-water sponges (Phylum Porifera) in the Canadian Arctic has historically been overlooked, in part because of difficulties associated with sampling deep hard bottom environments. Sponges for this project were obtained from 2015/2016 Amundsen cruises in the Canadian Arctic and Subarctic. This work spans three marine bioregions, which are thought to contain few (< 35) total known sponge taxa (Van Soest et al., 2017). Of the 38 examined so far, spicule-based identifications suggest there are at least 23 species from 17 different sponge families, several of which may be new species records for the region. Sponges hitherto known only from the Northeast Atlantic and higher Arctic (*Axinella arctica*, *Janulum spinispiculum*, *Mycale lingua*, and *Tetilla siberica*, among others) are reported for the first time from the Labrador Sea and Davis Strait. Already these results substantially increase our knowledge of sponge species richness on the Northeast Canadian shelf. Sponges are also being quantified from the ROV video to give an indication of species richness and biodiversity at some of the sites and to facilitate species identification for specimens collected in ROV surveys. This work will analyse sponge distributions by habitat and substrate type. This comprehensive taxonomic study has revealed new distribution ranges and enhanced our knowledge of the richness of sponge species in the eastern Canadian Arctic.

Other relevant results

- Dinophyceae from deeper than 100 m are dominated by parasitic taxa that could potentially infect deep sea corals and sponges (Deo Onda-PhD thesis chapter).
- Chytrid fungi are an underestimated source of upper ocean phytoplankton mortality (Comeau et al. 2016), which could have an impact on the delivery of organic matter to the deep ocean.
- The summer species composition of the two sides of Baffin Bay, differ with diatoms on the Canadian side dominated by *Chaetoceros gelidus*, in contrast to the Greenland side dominated by potentially noxious *Pseudo-nitzchia* spp.. The relative proportion of diatoms also varied over small spatial scales, consistent with very local patches of dominant species, with implications for the quality and food exported to the benthos (Nathalie Joli, PhD thesis Chapter).
- Preliminary results suggest an unsuspected diversity of thyasirids in Frobisher Bay, with some species being symbiotic, and others asymbiotic.
- ROV video is providing an index of sponge abundance along the sampled area.
- The three piston cores from the Disko Fan site penetrated locations on small ridges, with two cores on one ridge, and the third core on a different ridge about 500 m distance. It is possible that the ridges may have been made by accumulation of baffled sediments among corals, analogous to the growth of *Lophelia pertusa* cold-water coral reefs (e.g. Titschak et al. 2015). Piston cores were returned to the Geological Survey of Canada (Atlantic) and X-rayed before sectioning. Of the three cores, only core 2016804014 penetrated buried bamboo coral thickets. Bamboo coral fragments were found to ~50 cm depth in the main core, and to 130 cm in the trigger-weight core, which typically loses less fine-grained material from the surface. The deepest coral fragments recovered in the cores were found immediately above the shallowest glaciomarine till tongue sediments, suggesting that the bamboo coral forest has been growing at this location for several thousand years, at least. Radiocarbon analysis of buried coral fragments within the piston cores, noting depth of fragments, will be used to assess sediment accumulation rates and, more significantly, the time span over which the *Keratoisis* coral forests have been growing.

CONCLUSION

Invertebrates and fish diversity

- Corals were abundant and diverse at most of the sites surveyed, especially at the site based on fisheries observer bycatch (ROV5) and the sites based on scientific survey trawl bycatch (ROV3, ROV7). The southern sites were visually dominated by the large calcareous gorgonian coral *Primnoa resedaeformis*, but hosted a high diversity and abundance of other corals including smaller gorgonian corals, soft corals, and occasional sea pens. Stylasterid corals were observed in the box cores from site ROV3, constituting a biogeographic range extension. Similarly, a white variety of *Paragorgia* sp. observed at this site represents another range extension, indicating the importance of NE Saglek bank for both abundance and diversity of corals.
- The diversity of sponges, corals, other invertebrates and fish was documented at all surveyed sites. These observations indicate high sponge concentrations and species richness in all sites, not only in the SE Baffin shelf site that was chosen for sponge bycatch. Evidence of fishing impacts at these site was documented in the form of trawl door scars and broken sponges, although this site appears to fit within a gap in fishing effort, when compared against maps of fishing effort compiled for the NW Labrador Sea.
- Observations show corals co-occur with sponges as well as other benthic animals (e.g. fish, octopus, basket stars, shrimp, hydroids, brittle stars, sea anemones, and bryozoans).

Steep/deep versus gravelly bottom sites

An array of bottom types were observed in all five sites, from muddy bottoms to bedrock outcrops. The benthic fauna associated to the different bottom types was also distinct and dominated by different organisms, indicating the need to sample both types of habitats (e.g. soft and hard bottoms).

ROV performance, sampling elevator system and new sampling skid

The elevator was not deployed, due to the inconsistent and unreliable performance of the ROV. Being unable to use the elevator, and not having a second dive at any of the sites except ROV7, meant that it was not possible to deploy the paired current meters or paired settlement and carbonate taphonomy experiments. By contrast, the new sampling skid worked very well, allowing multiple collections in good condition at almost all sites. Unfortunately, the hydraulic system of the new elevator lost hydraulic oil, and may have contributed to the limited length of dives at almost all sites.

Box cores

Box cores planned in association with most of the dive sites were successfully collected, and represent an important additional data source. Even though many of the sites had gravel or cobble bottoms that limited box core penetration, the box cores yielded important samples that provided evidence of higher biodiversity importance of these sites than documented from the ROV alone. The combination of megafaunal surveys from the ROV video with direct sampling from the box cores is particularly powerful.

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REMOTE SENSING OF CANADA'S NEW ARCTIC FRONTIER

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Validation d'un modèle de production primaire satellitaire pour l'océan Arctique : éclairement incident et réflectance marine
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Variability of Arctic ice edge blooms and the implication for the biological pump in a period of declining ice cover
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ABSTRACT

In most parts of the World Ocean, the phytoplankton spring bloom (PSB) provides a large fraction of the annualprimary production (PP) and, most importantly, nearly all of the new PP exportable through the food chain and toward the bottom sediments. In the Arctic Ocean (AO) the PSB often develops around the ice-edge. This highly transient phenomenon lasts about three weeks at any given location in the seasonal ice zone (SIZ) and accounts for most of the annual PP in the AO. The SIZ is currently increasing in size and may cover the entire AO as of the 2030s. Therefore, one may wonder whether ice-edge blooms will cover a much larger area than they used to through a significant northward expansion. If so, what will be the fate of this additional phytoplankton biomass build-up along the retreating ice cover. Will it sustain higher secondary production and trophic transfer in the pelagic food web, thus benefiting megafauna? Or will it sink rapidly and create new benthic hotspots, possibly contributing increased carbon sequestration in the sediment? The overarching goal of the present project is to understand the processes that control the Arctic PSB as it expands northward and to determine its fate in the ecosystem by investigating its related carbon fluxes. The short-term objective of this project is to understand the dynamics of the Arctic PSB and, more specifically, how it is controlled by physical and chemical properties of the upper ocean and by phytoplankton species succession during the bloom. The long-term objective is to determine the fate of the PSB in a changing AO. We hypothesize that PP at high latitudes will increase in the coming decades because of a northward expansion of the SIZ and an intensification of the PSB. Changes in the phytoplankton phenology may have profound consequence on the entire ecosystem and food chain.

A PSB event will be monitored in Baffin Bay from its onset under melting ice in May to its conclusion in the SIZ in July. Relevant physical, chemical and biological properties will be described at various scales using profiling floats, gliders and an autonomous underwater vehicle, equipped with physical and bio-optical sensors. Process studies will be conducted to document phytoplankton growth, nutrient assimilation and carbon transfer through the food web and towards the sediment. Key phytoplankton species will be isolated and grown under laboratory conditions to model their species succession and response to environmental factors. We will use ocean color remote sensing to thoroughly study the Arctic PSB, the full phenology of phytoplankton biomass, as well as transient phytoplankton blooms triggered by forcing events such as shelf-break upwellings. The optical properties of seawater in the vicinity of the ice edge and their variations during the PSB will be used to optimize our ocean colour algorithms and we will establish a time series of pan-Arctic PP over the period for which remotely sensed ocean colour data are available. The project is an unprecedented effort for gaining a mechanistic understanding of the PSB in the AO through the use of state-of-the-art field and laboratory observation technologies, remote sensing of ocean colour and sophisticated modelling tools. The knowledge gained from this project will expand our observational capacity and knowledge of the rapid changes taking place in Arctic ecosystems.

KEY MESSAGES

- The phytoplankton spring bloom (PSB) accounts for most of the annual PP in the Arctic Ocean and, more importantly, nearly all of the new PP exportable through the food chain and toward the bottom sediments.
- The Arctic PSB develops around the ice-edge in the seasonal ice zone (SIZ).
- The PSB is highly transient and lasts for about three weeks at any given location.
- The SIZ is currently increasing in size and may cover the entire Arctic Ocean as of the 2030s.
- Ice edge blooms should cover a much larger area than they did in the past due to a significant northward expansion.

- It is important to understand the fate of this additional phytoplankton biomass build-up along the retreating ice cover.

OBJECTIVES

As specified in our funding proposal, we aim to:

1. Understand the key physical, chemical and biological processes that govern the Phytoplankton Spring Bloom (PSB);
2. Identify the key phytoplankton species involved in the PSB and model their growth under various environmental conditions;
3. Determine the transfer of carbon produced by the PSB through the food web and towards the bottom sediments;
4. Document trends in the spatial and temporal variations of the PSB; and
5. Predict the fate of the PSB over the next decades.

KNOWLEDGE MOBILIZATION

- Presentation of preliminary scientific results at meetings of the GreenEdge consortium in Paris (November 2015) and Nice (December 2016)
- 14 presentations at scientific conferences
- 3 scientific articles (with review)
- 5 presentations for the general public (Québec)
- 3 presentations in the community of Qikiqtarjuaq, NU
- 2 presentations for the general public (France)
- 4 presentations in schools in Québec
- Web broadcast of presentation for 51 schools in France (October 2016)
- Outreach program in French schools (May-October 2016) – In the wake of an icebreaker http://www.greenedgeproject.info/icebreaker.php
- Participation in 24 h de science (May 2016)
- Outreach program in Inuksuit school, Qikiqtarjuaq, NU (April-June 2015, May-June 2016)
- GreenEdge blog 2015 https://greenedgeproject2015.wordpress.com
- GreenEdge blog 2016 http://greenedge-expeditions.com
- GreenEdge Website http://www.greenedgeproject.info/
- AOA, Arctic scientific adventures educational website http://aoa.education/fr; http://aoa.education
- Canal savoir report http://www.canalsavoir.tv/videos_sur_demande/larecherchepardelalesfrontieres (Timecode 16:39 Takuvik)
- http://www.consulfrance-quebec.org/La-recherche-par-dela-les-frontieres-l-emission-qui-vous-emmene-au-coeur-de-la
- Teaser for Documentary film Arctic Bloom – Tuvaq, À l'orée de la banquise https://vimeo.com/163206186

INTRODUCTION

In the ocean, as in terrestrial environments, the food chain mostly relies upon the input of energy and organic matter at the level of so-called primary producers that achieve photosynthesis. Any significant change in PP will therefore have an impact on the entire food chain, from zooplankton to birds and mammals. Phytoplankton is responsible for most of marine PP. Its growth largely depends on available inorganic nutrients and light, and on temperature. In the Arctic, the place on Earth where climate change causes the deepest and fastest changes in terrestrial and marine environments (Ardyna et al. 2011), how will marine PP respond and what will be the impact on the whole marine ecosystem? The Arctic Ocean is characterized by a high biogeographic complexity and the existence of distinct PP regimes (Ardyna et al 2013, Perrette et al. 2011, Tremblay and Gagnon 2009). Pan-Arctic PP distribution reflects the combined role of vertical stratification and nutrient availability (Perrette et al. 2011, Tremblay and Gagnon 2009, Carmack et al. 2006). Primary production in the Arctic is highly influenced by water masses and the presence of sea ice, which limits the penetration of sunlight and air-sea interactions. The September extent of the Arctic Ocean icepack has decreased by nearly 40% over the last three decades. The resulting increase in the penetration of sunlight in the water column may boost PP of phytoplankton and, thereby increase the overall biological productivity in the Arctic Ocean.

During the Arctic spring, when i) solar radiation becomes high enough, ii) nutrients are abundant in the upper water column, due to various vertical mixing processes over the previous fall/winter, and iii) the water column is stabilized by stratification, a phytoplankton spring bloom (PSB) develops, as it does at lower, temperate, latitudes. One major difference in the Arctic Ocean is that the amount of solar radiation that reaches the top of the water column is not only controlled by celestial mechanics and atmospheric phenomena, but it is also highly constrained by sea ice which melts between late spring and early fall. As a consequence, the Arctic PSB is generally delayed until the sea ice either transmits enough light or breakups. In advance of the PSB, ice algae (pennate diatoms) develop at the ice-ocean interface. Then, in situations when sea ice is bare (no snow), thin, and possibly covered by melt ponds and/or includes leads, the PSB begins under the ice pack (Wassmann and Reigstad 2011). During the PSB, the general succession pattern begins with ribbon forming pennate diatoms (e.g. *Fossula arctica* and *Fragilariopsis* spp.) followed rapidly by colonies of polar-centric diatoms (*Thalassiosira* spp. and *Chaetoceros* spp.) (Hodal et al. 2012, Lovejoy et al. 2002, von Quillfeldt 2000). The PSB may end before ice breakup, continue to flourish, or start after breakup, forming a so-called ice-edge bloom. Ice-edge blooms tend to form a lateral band about 100-km wide, that follows the retreat of the ice-pack during spring in the SIZ. At any given location, after the PSB, the surface layer becomes nutrient depleted, and a so-called subsurface chlorophyll maximum develops around the depth of the pycnocline, which more or less corresponds to the nutricline (Lee et al. 2010). This oligotrophic regime lasts until fall when a limited bloom may take place at the lowest Arctic latitudes, before autotrophic growth shuts down for the winter.

2016 ACTIVITIES

Ice camp

Outside of the field season (mid July 2015-mid April 2016), Eric Brossier, a GreenEdge collaborator who was a year-round resident of Qikiqtarjuaq, installed and maintained a meteorological tower and camera equipment that monitored the evolution of ice retreat/formation. He also did the advance work (securing housing and truck, snowmobile maintenance, reconnaissance of field sites) in preparation for the arrival of our field team on April 20, 2016.

The field work was carried in the vicinity of Qikiqtarjuaq, NU (Figure 1) between April 27 and July 27, 2016. Over the 109 days that GreenEdge researchers were in the community, 52 people participated in ice camp operations. Thirty seven stations were sampled, including five from an air-boat (11-22 July). As part of work package 7 (local knowledge), eight local hunters of varying ages were interviewed in the community to get their opinion about changes in hunting and fishing practices over time. In late May, three GreenEdge researchers accompanied 12 Inuit to a hunting camp to get first-hand knowledge about the impact of ongoing climate change on their traditional hunting territory. This was documented by a film crew and will be integrated into a 52-minute documentary that will be completed in the autumn of 2017.

The ice camp operations summarised in Figure 2 were conducted in and around a PolarHaven tent and a wooden cabin mounted on a sled. Operations in the tent included:

- CTD- Underwater Vision Profiler (UVP)
- Seawater sampling with 8 L and 20 L Niskin bottles at six depths, with one deep profile/week
- DIC, TO-DOC, sugar, and nutrient sampling
- Collection of pooled water in 20 L jugs for stock measurements back in the lab
- Measurement of Inherent Optical Properties (IOP) using instruments mounted on an optical frame (LISST, BB3, BB9 and CTD)
- Deployment of nets for phytoplankton and zooplankton sampling, and
- Monitoring of a 13-hour tidal cycle on June 23, 2016 using a CTD, BB3 and SCAMP

The PolarHaven tent was dismantled on July 10.

Operations in the wooden cabin included:

- Physiological measurements of ice algae and phytoplankton under controlled conditions (light and nutrients)
- Filtration for HPLC analyses, and
- Determination of nutrient stocks

The cabin was towed back to shore on July 4.

On-ice operations conducted outside the tent included:

- C-OPS measurement of Apparent Optical Properties (AOP)
- Under ice PAR measurement
- Extensive ice coring
- Nutrient bioassays on under ice communities

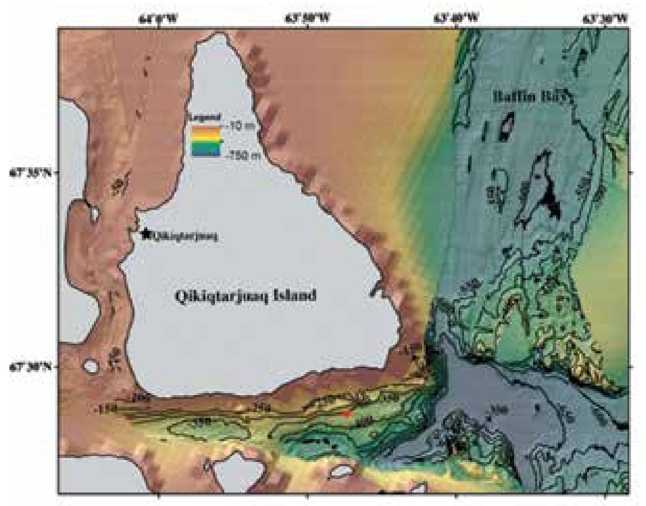

Figure 1. Map showing the location of the ice camp (red dot) south of Broughton Island 67˚28.784N, 063˚47,372W). Bathymetric data is from the high resolution multibeam echosounder installed aboard the CCGS Amundsen (credit: Gabriel Joyal and Patrick Lajeunesse) and the International Bathymetric Chart of the Arctic Ocean (IBCAO).

- Under ice incubations (production)
- Imaging and measurement of under ice light with a ROV
- Measurement of snow optical properties
- Sediment traps
- Temporal series of images using a drone, and
- Meteorological station measurements

Pooled water and other samples were brought back to the laboratory at Inuksuit School in Qikiqtarjuaq for further analyses and storage, including:

- Spectrophotometer (Particulate Absorption)
- Image FlowCytoBot (Taxonomy)
- Microscopy (Cell isolation and imagery)
- Incubation chamber, cell growth (phytoplankton)
- Ultrapath (Colored Dissolved Organic Matter (CDOM)

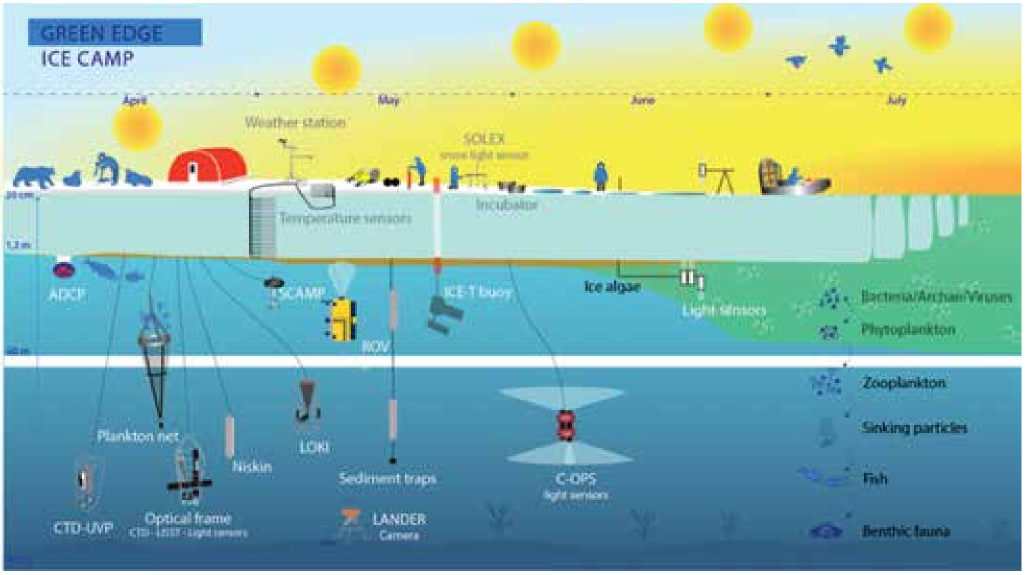

Figure 2. Visual summary of the instruments used during GreenEdge ice camp operations in 2016 (credit: Julie Sansoulet).

- Filtration (Ap, CHN/SPM, CDOM, Silice, genetic, sugar)
- Salinity ice cores, and
- Conservation of samples (freezing, refrigeration)

Oceanographic campaign (CCGS *Amundsen*)

The GreenEdge team was aboard the CCGS *Amundsen* for Leg 1 of the 2016 season (June 3-July 14). Thirty six of the 41 day-leg were dedicated to operations. Seven transects, 0.5° of latitude apart, were made in central Baffin Bay. Over the 33 days of sampling, a total of 135 were visited, including Full (28), Basic (19, AOP and core sampling), Nut (44, nutrient & DIC) and CTD only (42). The sampling grid is indicated in Figure 3. A visual representation of the equipment used during the cruise is illustrated in Figure 4.

On-board operations:

- MVP transects in open waters
- Deployment of 5 Bio-Argo floats
- Deployment/Recovery of 2 Slocum gliders
- Deployment of 5 ISVP buoys
- Deployment of 2 drifting sediment traps
- 203 CTD/RO casts
- 16 Agassiz trawls
- 34 box cores
- 6 Beam trawls
- 6 IKMT trawls
- 16 Tucker net trawls
- 10 Hydro-Bios net deployments
- 22 LOKI deployments
- 35 AOP casts
- 28 IOP casts
- 11 Ice operation activities
- 14 Bird sampling activities, and
- 26 SCAMP deployments

Continuous measurements:

- Geographic location of ship
- Met tower data, irradiance, total energy

- 360° time lapse photos around ship
- bottom mapping
- s-ADCP, and
- pCO_2 – carbonate system

RESULTS AND DISCUSSION

Upper ocean physics of Baffin Bay marginal ice zone

Fluorescence data indicated that the underice bloom that develops at the surface deepens as we move further away from the ice edge. The use of Slocum gliders enabled us to identify fine scale features and Bio-Argo float data will provide a long-time series including a characterisation of the water column in the fall. Upwelling features at the ice edge drive the upward velocity of tracers, including nutrients and phytoplankton and the sinking of surface waters. Primary production is large in the coastal ocean near topographical features and the ice edge. Fine scale signature of physical properties of the water column were shown through MVP data. The presence of fronts is indicative of a strong baroclinic activities in the upper ocean layer. A physical paper on upper ocean physics is in preparation. It will document the physical context in which the phytoplankton bloom was observed during the GreenEdge project. A second paper will document findings from ice camp activities.

The SCAMP was deployed at almost every FULL station, providing fine scale vertical data to a depth of 100 m. From the CTD data, features of instability in the water column were identified. Ice concentration had an impact on the amount of turbulence. The main variable measured is the SCAMP is the turbulent kinetic energy dissipation rate (ε), which showed variability at fine spatial and temporal scales. A high dissipation was associated with convective instabilities in the top 30 m. Calculations of the turbulent diffusion coefficient and strong upward diffusive nitrate fluxes showed a sharp nitracline at many stations.

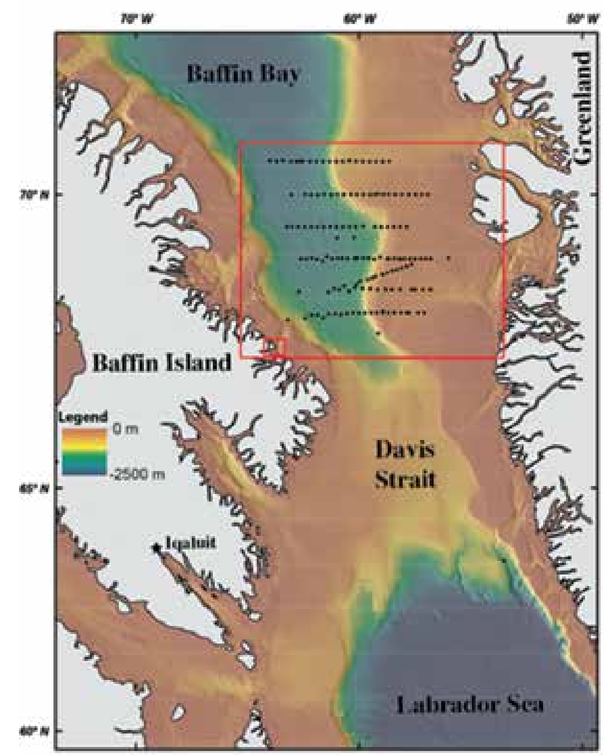

Figure 3. Map illustrating the sampling grid used during the GreenEdge oceanographic cruise on the CCGS Amundsen (red square). Bathymetric data is from the high resolution multibeam echosounder installed aboard the CCGS Amundsen (Gabriel Joyal and Patrick Lajeunesse) and the International Bathymetric Chart of the Arctic Ocean (IBCAO).

Modelling Activities

The 1D model coupling with PISCES started running in January and should be completed by early 2018. The 3D physics modeling (1/4° NEMO/LIMZ), should be completed end of 2017 and the 3D Pan Arctic IPCC run (NEMO/PISCES) by the end of 2018. The issue with the last approach, is the forcings are not easy at the boundaries, so it may be easier to use a global model and then focus on the Arctic, which raises questions as to how to account for ice and the intricacies of the physics and biology of Arctic marine ecosystems.

The Darwin model is being used to provide distribution and abundance of phytoplankton

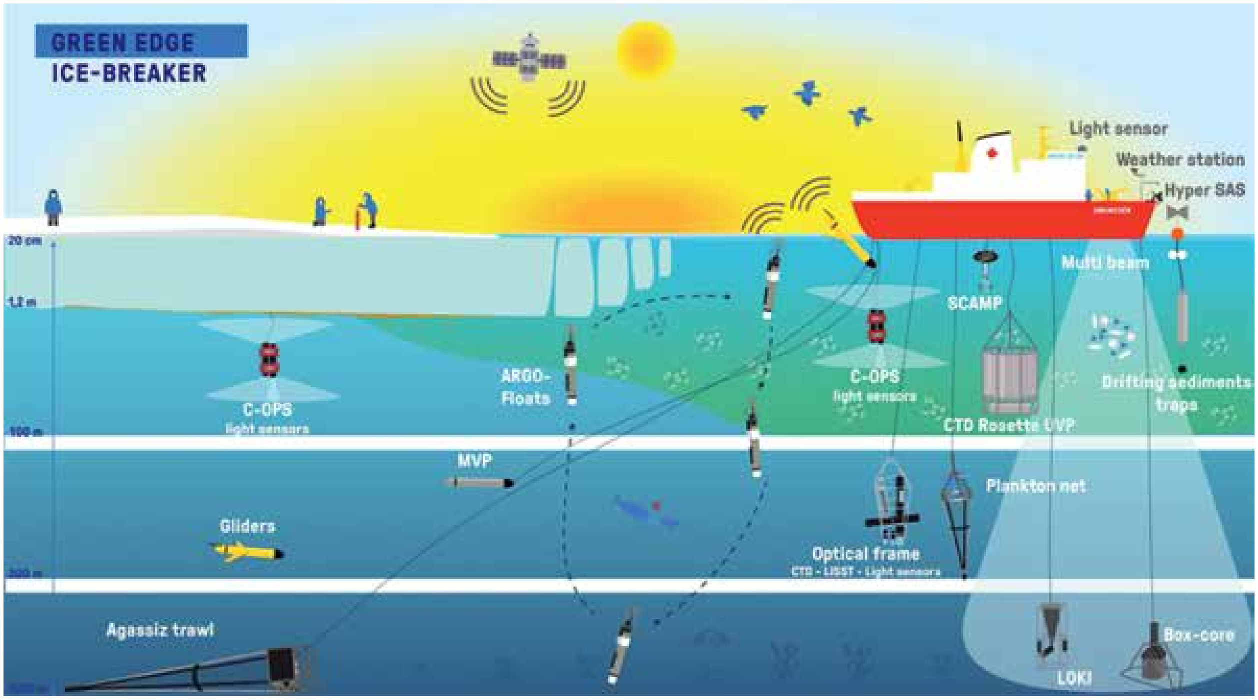

Figure 4. Visual summary of the equipment used during the GreenEdge oceanographic cruise (credit: Julie Sansoulet).

functional groups, with results validated from moorings and later applied to Baffin Bay. Preliminary results show a variability in the phytoplankton functional groups and will be compared to groups identified through HPLC or taxonomic counts. Linear Inverse Modeling (LIM) is being employed to reconstruct food webs. Through the ecological network analysis (ENA), carbon flows through the food web can be ascertained, providing information on how feeding interactions are distributed between trophic levels.

Optics and Remote Sensing

Remote sensing data that is available daily, is being used to characterize the state of the atmosphere during the 2015 and 2016 field campaigns. These data, including cloud fraction, cloud optical thickness, sub surface temperature, windspeed, sea ice extent and sea ice concentration will be exploited to support in situ measurements. The 360° Ice-Cam images (n=12066) taken from the *Amundsen*, have been assembled, providing a visual record of ice movement and concentration over the field campaign in Baffin Bay (Figure 5).

Variations in the quantity and quality of light regime under the ice has a direct influence on the dynamics of the PSB. In 2016, ice-melt was relatively late. By mid-June, the snow cover was relatively thin (0-3 cm), melt ponds were beginning to form and air temperatures were 5°C (day) and 0°C (night). This corresponded with changes in the water column. For example, the depth of the mixed layer rapidly decreased from 25 m to less than 10 m, with an increase in stratification index (Brunt Vaïsaïla frequency; $N2 > 5x10^{-3}\ s^{-2}$). This very stable surface mixed layer was generated by melting of the ice sheet, as observed by a lower potential density ($<26\ kg\ m^{-3}$; Figure 6).

These conditions resulted in an increase in the concentration of chlorophyll a (Figure 7) and the proportion of concentric diatoms (Figure 8) such as *Thalassiosiara* sp and *Chaetoceros* sp. These are typical pioneer species that colonize the water at the beginning of the bloom. In both 2015 and 2016, phytoplankton growth showed a marked increase at the beginning of July (Figure 6).

A tight relationship was found between ap(443) values and Tchl *a* concentrations in samples obtained during the *Amundsen* cruise and was not significantly different from relationships previously derived for the Arctic ocean and temperate/tropical waters. The contribution of non-algal particles to particulate absorption (anap/ap (443)) tends to increase with Tchl *a*, varying between 5 and 25% in the surface layer. The aphy vs Tchl *a* relationship is slightly different from previous studies in the Arctic Ocean and varies greatly from studies in temperate and tropical waters.

Preliminary results of the light absorption properties of particles and colored dissolved matter the spring bloom was well captured in ap (λ) values, but not in a_{CDOM} (λ) values (Figure 9). The relationship between a_p(443) and fluorometric chl *a* concentrations in the water column are consistent with published findings, but show high scatter. The a_p(443) values in ice cores were well above those observed in the water column (Figure 10).

In 2016, apparent optical properties (AOP) were measured *in situ* both at the ice camp (84 good profiles, 29 different days, May 4- July 18) and during the *Amundsen* cruise (34 profiles, 11 stations, June 12- July 3) using a C-OPS and Ice-Pro instruments, providing a profile of downward and upward marine irradiance. A bump was seen in the red part of the spectrum at depth when phytoplankton bloomed at depth. The blue and green irradiance showed similar patterns. The vertical diffuse attenuation coefficient (Kd) for blue and green parts of the spectrum increased to depth with time whereas the red Kd was very noisy. Ice camp measurements of Kd show a nice time series for the different wavebands, with a significant increase in Kd in July, indicating the onset of the PSB. The signal to noise ratio (SNR) showed also increased with depth.

Figure 5. Image produced by the 360° ice-cam on the CCGS Amundsen, the result of 12 images taken simultaneously every 5 minutes (credit: Philippe Massicotte).

The use of a Remotely Operated Vehicle (ROV), a drone and a cosine camera enabled us to conduct light measurements below the ice at the ice camp. Ice thickness did not vary spatially over the study area. Vertical profiles of light were directly affected by distribution of melt ponds, cracks and ridges. Patterns of ice algae growth were related to the presence of brine channels.

Gliders and Floats

Given that gliders and floats remain in the water for prolonged periods, they provide information that complements the observations obtained through remote sensing and standard in-situ oceanographic measurements.

Two gliders were deployed from the *Amundsen* in 2016. Chlorophyll-a fluorescence showed mostly sub-surface phytoplankton bloom in open ocean whereas the bloom was much closer to the surface when under the ice. The ice edge moved significantly during their deployments. The two gliders were deployed on parallel transects about 20 km apart (Figure 11) and showed similar patterns, although fine scales showed more variability for most variables. The Five Pro-ice platforms were deployed in Baffin Bay in 2016. This is in addition to the floats deployed in 2015 (2) and those planned for the future (2017 (7); 2018 (6), for a total of 20 floats). These BioArgo floats are equipped with ice detectors, which prevent them from surfacing under ice cover and damaging their payload. However, the

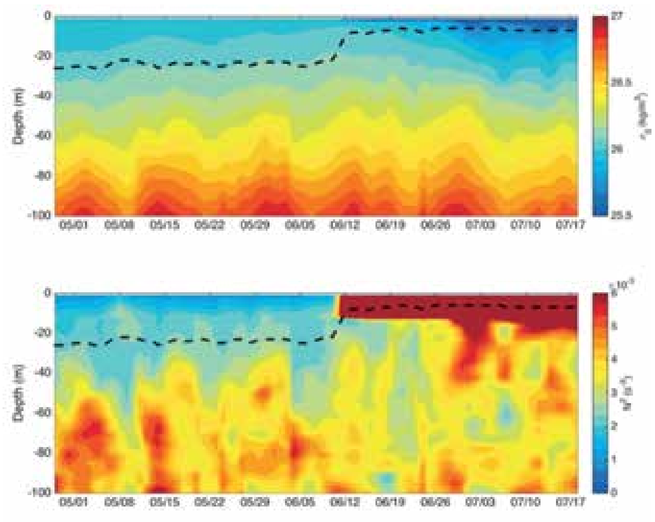

Figure 6. Times series of the potential density of the top 100 metres of the water column (upper panel) and the Brunt-Väisälä frequency (bottom panel) at the ice camp in 2016. The dotted line represents the mixed layer depth (credit: Laurent Oziel).

sensors also prevent transmission of data by iridium satellite communication. The float deployment sites were identified through modeling exercise of the circulation pattern in Baffin Bay, Observations from the different sensors show seasonal variation of the different variables. A deepening of the DCM during spring and summer, with a shallowing and decreasing of the DCM in the fall. Although the floats show time-series, they are also affected by 3d features. The depth of the deep chlorophyll maximum (DCM) does not seem to be related to nutricline but rather to the depth of the available incident irradiance. Averaged [O_2] in the mixed layer began to increase in September after a marked decrease in July and August. [NO_3] concentration also showed an increase in the fall as the mixed layer deepened.

A float-glider inter-calibration showed very similar features for most variables. A distinct mass of cooler, fresher water was observed at depth in water near the east coast of the Baffin Bay, which is an unidentified water mass from an undetermined source. When compared to World Ocean Atlas climatology, large variation was found, prove the needs to verify these measurements.

Biodiversity

Cultures were obtained both from the *Amundsen* (water column) and ice camp (water column, melt ponds and ice cores). A total of more than 1,000 cultures were obtained, they have been identified and molecular (18s) approaches were applied. The identified cultures included groups of Micromonas, Diatoms, Prasinophyceae and Fragilariaceae (Figure 12). Other markers are planned to be applied on the cultures such as 28s and ISSR. Scanning electron microscope imagery will be applied to the cultures to investigate the diversity.

Flow cytometry is used to enumerate specific populations of phytoplankton. A temporal series of pico and nano phytoplankton at the 2015 ice camp showed blooms of both appearing in July, although it seems that the picophytoplanton bloomed prior to the nanophytoplankton. Two bacterial population were identified (high and low DNA population). Maps of the abundance of nanophytoplankton, picophytoplankton and bacteria showed the distribution in the Baffin Bay from the 884 samples collected over 34 days on the *Amundsen* (Figure 13). We successfully captured prebloom, bloom and post conditions, from under ice to open water. Nanophytoplankton were found during the prebloom, nicophytoplankton, picophytoplankton and bacteria were present under the bloom conditions and nanophytoplankton and bacteria during the post bloom period.

During the 2016 field campaign, a total of over 425,00 Imaging Flow Cytobot (IFCB) images were produced from water column, ice core, sediment trap, melt pond and experimental samples collected at the ice camp (352 samples) and Leg 1b of the *Amundsen* cruise (264 samples) to ascertain phytoplankton diversity. Images are automatically analysed for 200 parameters in EcoTaxa (Laboratoire d'océanographie de Villefranche (www.ecotaxa.obs-vlfr.fr) (LOV, CNRS) and are later manually validated. Most can be identified to the genus level. Analysis and validation is ongoing and should

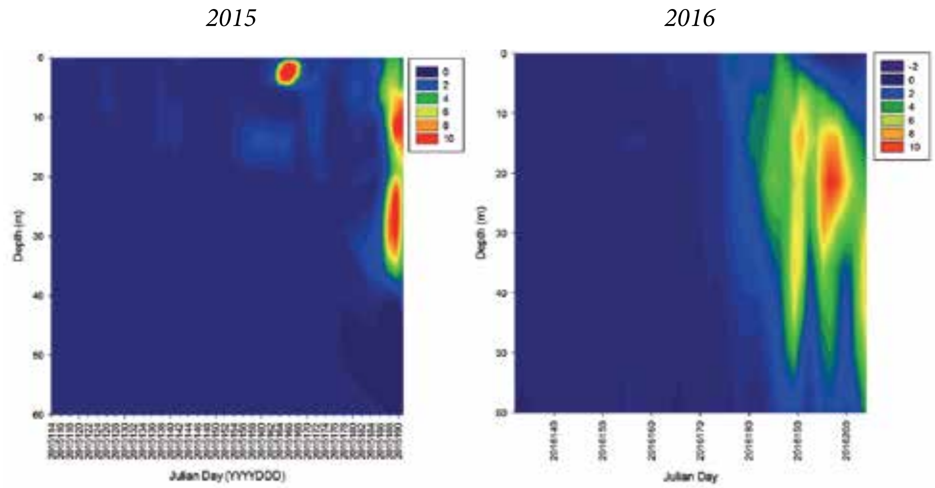

Figure 7. Concentrations of Chl a (mg m^{-3}) as an indicator of phytoplankton biomass (credit Joannie Ferland).

be completed during the winter of 2017. Preliminary results from the Transect 6 of the *Amundsen* cruise showed an increase in *Pheocystis* related to an increase in DMS concentration.

Preliminary results for HPLC analyses from the 2016 ice camp show an increase in chl *a* in the water in early June (Figure 14). Results from the ice cores showed an increase in concentration at end of May on the 0-3 cm layer. The photoprotection index in the ice core show an increase starting in early May. A predominance of microphytoplankton was found in both ice and seawater at the ice camp and in *Amundsen* samples. Results from the *Amundsen* show high concentration of Tchl *a* near the ice edge. There was a significant spatial heterogeneity in the distribution of phytoplankton populations. The phytoplankton maximum was at the surface under the ice, progressively deepening eastwards in ice free waters, with an increase in the contribution of microphytoplankton. Ice covered waters were dominated by picoplankton and crytophytes. A comparison between HPLC pigment and fluorescence profiles from the floats showed a discrepancy at very high concentrations of chl *a*. *Amundsen* and ice camp data should be fully validated by January and March 2017, respectively.

Biodiversity of Zooplankton

Despite the high diversity of Arctic waters relative to the Atlantic and Pacific regions of Canada, only a few key species of fish and zooplankton are important for carbon transfer purposes. Arctic Cod is the main species of interest in Baffin Bay. It is estimated that a total of 4,600 benthic species are present in Arctic waters. Trawl data from the GreenEdge cruise will be used to monitor the estimated 4,600 benthic species present in Baffin Bay diversity. A macrobenthos catalogue is currently being developed for West Greenland waters.

An Underwater Vision Profiler (UVP) is used to count particles >100 µm and take images of aggregates and plankton >700 µm. Of the 187,000 images taken during the 197 casts during the GreenEdge oceanographic cruise in 2016, 87% have been analysed by ecotaxa@obs-vlfr.fr.

About 20 groups of plankton can be identified from this system. Data are available through greenedge@free.fr. Aggregates represent 80-90% of the images, diatom chains about 7%, copepod about 2-3%. Results show higher values of aggregates and diatom chains near the Greenland side of the transects. Copepods represent about 80% of the zooplankton present. Other

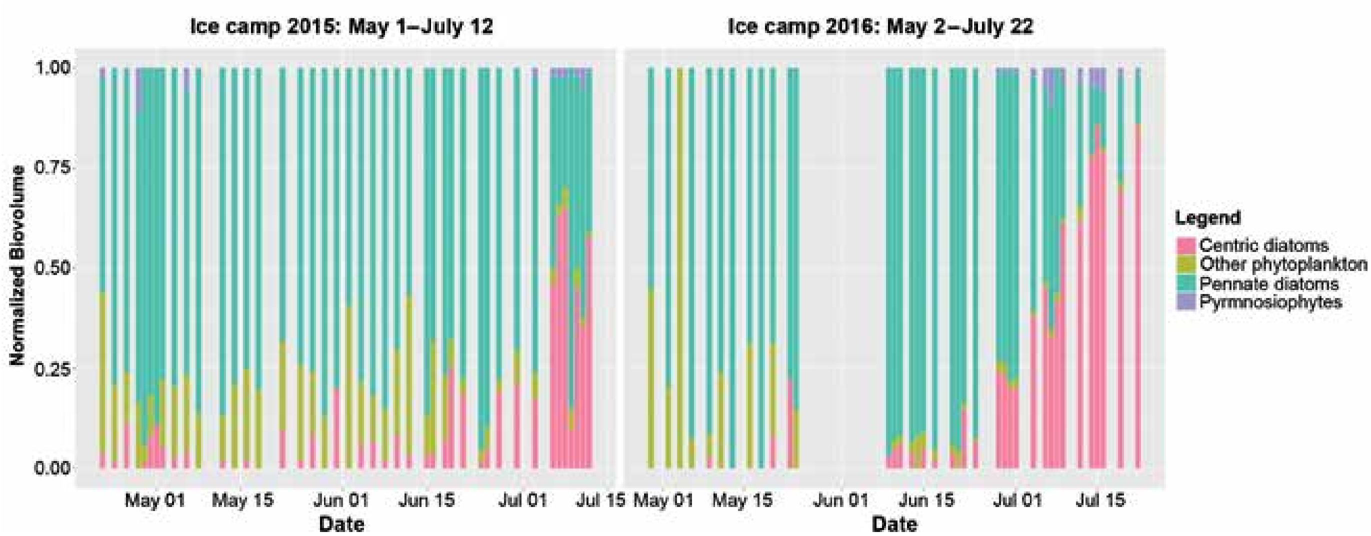

Figure 8. Proportion of diatoms relative to other taxonomic groups of phytoplankton in ice camp samples in 2015 and 2016 as determined with an Imaging Flow Cytobot (IFCB) (credit: Pierre-Luc Grondin).

zooplankton included *Acantharea*, *Limacinidae* and *Appendicularians*.

Contents of the zooplankton nets deployed from the CCGS *Amundsen* (primarily Monster + LOKI) revealed that 95% of the fish were juvenile Arctic cod. Of the adult population, approximately 75% were Arctic cod. A relationship was found between the presence of fish (determined by acoustics) and the bird populations (Thick billed murre, Northern fulmar, Black-legged killiwake) in parts of Baffin Bay.

Benthic diversity

The goal of the benthos group was to determine how the benthic community responds to different conditions of ice cover and primary production. Unfortunately, the Lander that was deployed near the ice camp did not function. Scherogeochemistry identifies trends in organic C produced over time. Results from *Mya truncata* species at the Qikiqtarjuaq site show high interannual variability in shell growth as a proxy for quality/quantity of diatom bloom. Since bloom timing is connected to break up, the relationship between shell growth and ice cover in a particular year will be investigated.

To determine the response of the benthos to organic matter pulses from the PSB, benthic sampling was carried out from the *Amundsen* at 12 sites using box corer, then cores were incubated. Variables analysed included nutrients and respiration. A map of benthic carbon demand showed higher demand on the shelf in post-bloom conditions. Aspects that may affect the coupling between the pelagic and the benthic ecosystems, timing, species, duration of the production, depth of the sea floor are important variables to take into consideration.

Nutrients cycling and primary production

Samples were obtained both from the ice camp and *Amundsen* campaign in 2016. Preliminary results from the 2015 ice camp 2015 showed reduction of nutrients in the water column (nitrate complete depletion), in early July. The nutrients from the ice cores showed a low nutrient concentration at the beginning and end of the ice sampling season whereas in high concentrations were found in May. DOC and DON concentrations in the water column were increased over the sampling season. In 2016, both the ice algae and phytoplankton bloom were captured. The *Amundsen* study looked at the distribution of nutrients and differentiated between new and regenerated production and looked at the impact of light on nitrogen uptake. A depletion of nitrate was found

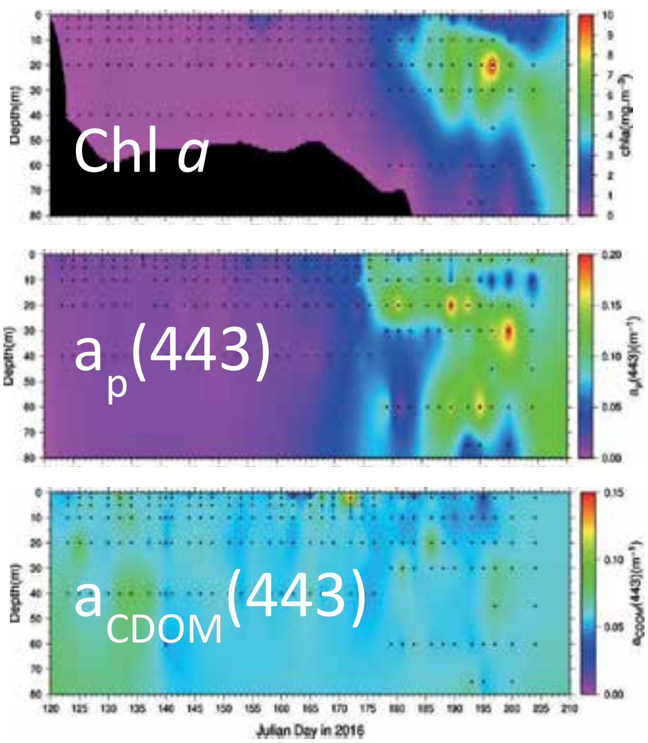

Figure 9. Evolution of chl a, ap(443) and a_{CDOM}(443) values over the 2016 field season. The PSB was well captured by a_p(443) but not by a_{CDOM}(443) (credit: Annick Bricaud).

on the eastern side of the Baffin Bay. Primary production profile showed variability, the pattern of which appears to be related to the proximity to the ice edge.

Silicates and diatoms

Operations including, *in situ* incubation with label 31Si and PDMPO staining were used to quantify silicate stocks and fluxes in samples from Arctic waters, ice and sediment traps. Ice core sampling in 2016 was performed under a tent the dark. At the ice camp, the temporal series in biogenic silicate stocks agreed with chl *a* patterns in the ice and water column. Production rates showed a very large peak in the water column on May 8 followed with another peak with the bloom, showing values in the range of Antarctica values or Bay of Brest under diatom bloom. An experiment of nutrient limitation (silicate) showed variability in the water column whereas in the ice there was only one peak around May 21. On the *Amundsen*, the integrated biogenic silicate showed high concentrations when integrated down to 200 m on the Eastern side of the Baffin Bay. PDMPO labelling permits newly produced silicate to be visualized (fluorescence), which can then be analysed by microscopy (Figure 15).

Bacterial community

Preliminary results from ice camp 2016 and the *Amundsen* campaign show a delay compared the chl *a* concentration time series. The integrated values of bacterial abundance and production show high spatial variability from the *Amundsen* dataset (Figure 16). Bacterial respiration was studied after 5-day incubations at 1°C. Respiration was measured on samples filtered at 1 µm, which results in a loss of respiration from large cells, resulting in BR=1-19.5 $\mu gC^{-1}d^{-1}$ (mean BA=32%, mean BP=19%).

Response of phytoplankton to light

PAM Fluorescence, measured both at the ice camp and on the *Amundsen*, provided information about photo protection and the photochemical efficiency (Fv/Fm). High Fv/Fm values were observed from early May to early June. The value collapsed in mid-June, probably due to photoinhibition or nutrient limitation. This decrease preceded the collapse chl *a* biomass by two days. To quantify the effects of high light on phytoplankton, a light shock was applied to samples. Fluorescence decreased brutally, followed by a full recovery when no repair inhibitor was added and a partial recovery when repair inhibitor was added. Photosynthetic parameters were assessed by production vs irradiance curves (P vs E) throughout the field season, on water and ice samples at the ice camp (105 water, 27 ice) and on the *Amundsen* (8-10 for each full station, 11 ice). Preliminary results show an increase in acclimation rate (Ek) around 160, which coincides with a decrease in fluorescence. The shape of the P vs E curves varied significantly between surface and 40m samples. Average Ek values for ice algae is around 40µE.

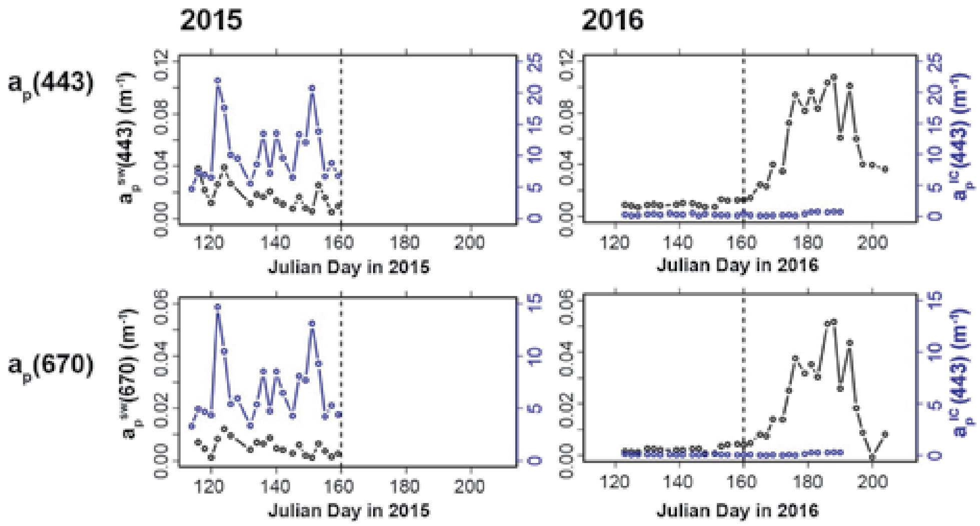

Figure 10. Variability in particulate absorption over time at the ice camp in 2015 and 2016. Black dots represent samples from the water column and blue dots represent ice core samples (credit: Annick Bricaud).

Experiments conducted at the ice camp aimed to assess the differences in photoprotection of ice algae and phytoplankton. Photo-protective pigments were produced and the xanthophyll cycle was activated prior to the thinning of the snow cover. Ice-algae showed a very high level of resilience after light stress. A time series of photosynthetic parameters from water and ice samples show that water column samples show an adaptation to higher light level than the ice samples, which is counter intuitive.

Sources of DMS

DMS plays a role in both climate regulation and marine physiological processes. From ice cores, profiles of DMS show generally an increase at the bottom of the ice core, but directly under bare ice, a large concentration of DMS was also found near the surface, indicating fluxes. Samples from under ice water and in melt ponds domes showed high values of DMS concentration. Similarly, DMS in melt ponds is high, which seems to be a 'new' source of DMS for the atmosphere. From the complementary experiments, a relationship was found between DMS and salinity, which means that the meltponds need to be 'fed' by sea water. The 'slush snow' seems to be a good source of salinity and DMS. From the *Amundsen* results, very high concentration of DMS was found in hot spots.

Paleoceanography

Cores have been collected at various sites along the Greenland coast. Sedimentation rates are

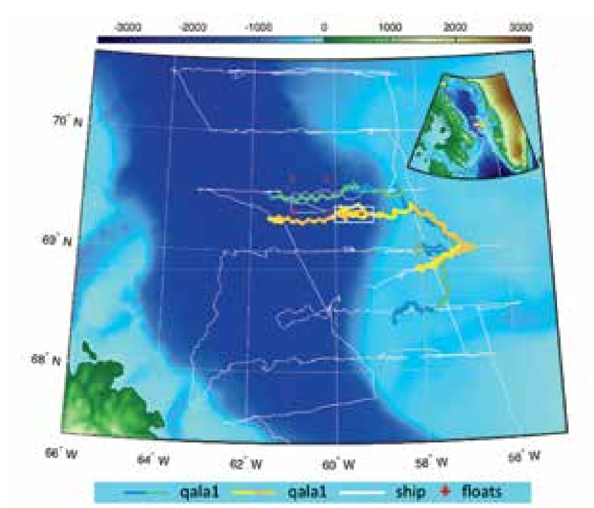

Figure 11. Transects of the two Slocum gliders (qala 1 and qala 2) in relation to the Pro-Ice deployment sites during the 2016 GreenEdge cruise.

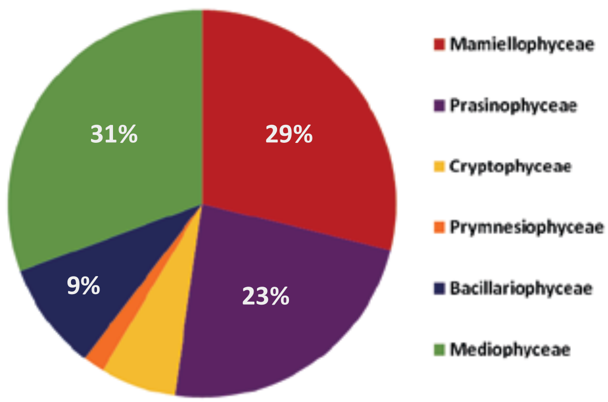

Figure 12. Phytoplankton biodiversity in areas of Baffin Bay studied during the 2016 GreenEdge field campaign.

generally low in Baffin Bay, providing a resolution of 6-24yr cm. Paleomagnetism may provide an alternative to complete the chronology. Foraminifera will be evaluated as their ecology may be a potential bio-indicator. Preliminary results show the distribution of calcareous and agglutinated Foraminifera species, with predominance of agglutinated species in most region except for the Kane 2b core, which may be an indicator of corrosive waters.

Local knowledge and food security

The model of food security is based on four pillars: i) quality, ii) quantity and availability, iii) access of food, and iv) preference. Different projects will address food security. Preliminary results from this latest study points towards a melting of the ice in the recent years, and more ice seem to be drifting from the North. There is also a noted decrease of snow cover. A large database of marine resources consumed by the Inuit has been put together. It is important to avoid generalisation, as knowledge will differ according to age groups, location, etc. Silence and observation is a key component in the Inuit culture. To develop the food security model, a post-doc will integrate the four pillars and the information from GreenEdge and IPY to develop indicators for food security using a Linear Inverse Model (LIM).

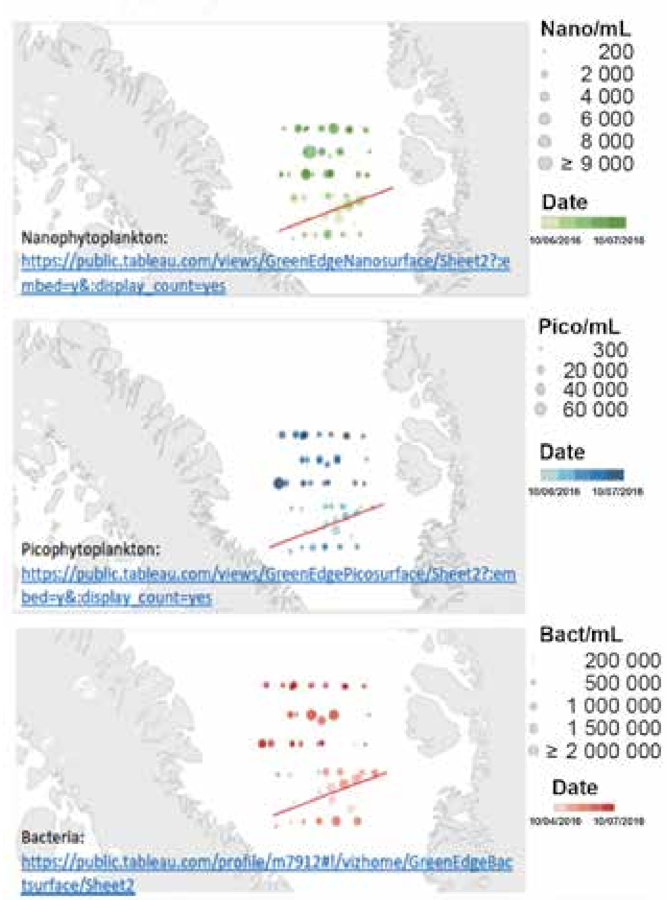

Figure 13. Maps of the cell counts of nanophytoplankton, picophytoplankton and bacteria at the surface along the 7 transects in Baffin Bay, leg 1, CCGS Amundsen cruise June 9-July 10, 2016.

Post campaign activities

Over 60 members of the GreenEdge consortium met in Nice, France December 13-15, 2016 to review preliminary results from the 2015 and 2016 field seasons. It was a chance for the working groups to meet face to face to plan analyses, modelling activities and the dissemination of results. Additional meetings are being planned for later in 2017. GreenEdge data is housed on the LEFE-CYBER site managed by Catherine Schmechtig (LOV). As data is cleaned and treated, the most recent version will be posted.

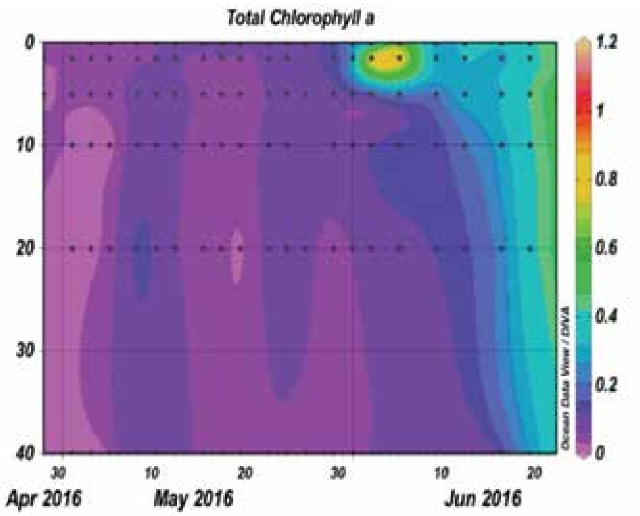

Figure 14. The spatio-temporal of total Chl a biomass as a function of depth at the 2016 GreenEdge ice camp.

Figure 15. Microscopy imaging of PDPO labelling (credit: Karine Leblanc).

CONCLUSION

Even though our analyses are still in the preliminary stages, we deem the project to be very successful. We correctly identified the spatio-temporel evolution of the bloom and were able to follow its progression in the seasonal ice zone in Baffin Bay. We have gained a better understanding of the physical and biogeochemical processes at the ocean/ice interface that trigger the onset of the bloom and govern community diversity and species succession as it develops. In the coming year, as we continue to analyze data and increase our modelling efforts.

A bloom of Phaeocystis, a genus of algae belonging to the Prymnesiophyte class, was observed during the *Amundsen* cruise. This is the first time that this has been documented in Baffin Bay. The genus is habitually found further south in the North Atlantic. Will the appearance of this 'exotic' species have an impact on biodiversity and carbon flux in Arctic ecosystem?

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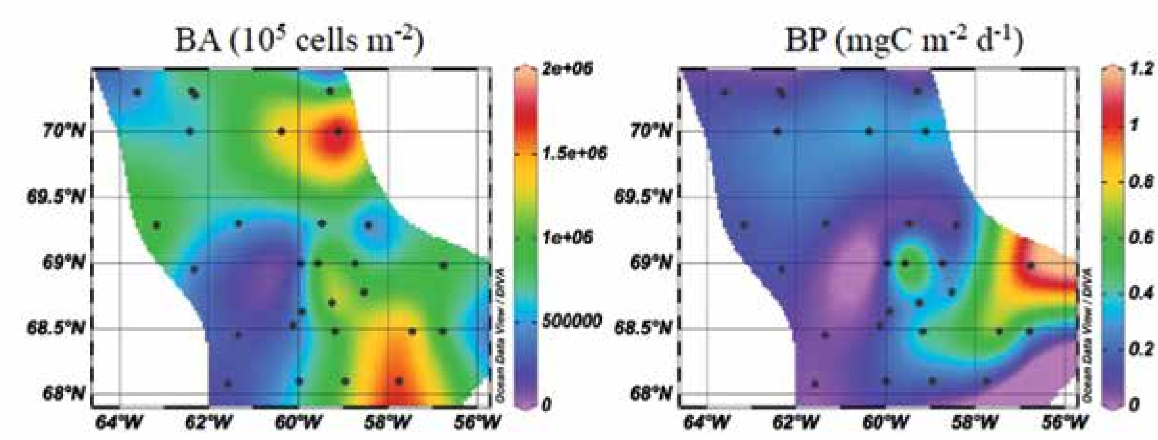

Figure 16. Spatial variability of bacterial abundance and production patterns from Amundsen Leg 1 2016 dataset.

Gagné, E. Devred and M.-H. Forget from the Takuvik laboratory, C.J. Mundy and V. Galindo from University of Manitoba & F. Pinczon du Sel and E. Brossier from Vagabond. We also thank Michel Gosselin, Québec-Océan, the CCGS *Amundsen* and the Polar Continental Shelf Program for their in-kind contribution in terms of polar logistics and scientific equipment.

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SEA ICE – UNDERSTANDING AND MODELLING OCEAN-SEA ICE-ATMOSPHERE BIOGEOCHEMICAL COUPLING IN A CHANGING CLIMATE

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ABSTRACT

Over this final cycle of ArcticNet we will continue to develop our understanding of how the atmosphere and ocean force sea ice dynamic and thermodynamic processes. We will model future changes in sea ice based on this knowledge and examine the consequences of this change on various aspects of ecological and geochemical cycles operating across the ocean-sea ice-atmosphere (OSA) interface. To accomplish this we intend to examine these interacting systems at a range of space and time scales, taking advantage of in situ experimentation, mesocosm studies, and model development.

KEY MESSAGES

1. During the past fiscal year (April 2016 – March 2017) we have produced over 35 peer-reviewed publications we have also presented at over a dozen different international conferences.
2. We have participated in six major field programs: SERF winter 2017, CCGS *Amundsen* ArcticNet Cruise summer 2016, Eureka Spring 2016, ASP St Nord field Campaign spring 2016, Cambridge Bay Spring 2016, and the Belcher Islands Campaign Spring 2016.
3. An inversion algorithm was developed to retrieve some geophysical parameters of the snow-covered landfast sea ice. The inversion results were improved by developing an enhanced volume scattering forward solver. Therefore, the salinity, temperature, and density profiles were reconstructed with a reasonable accuracy.
4. A passive microwave-based sea ice concentration dataset was used to characterize the timing of sea ice on the shipping corridor to the Port of Churchill between 1980 and 2014. Significant linear relationships were observed amongst breakup, freeze-up, and the length of the open water season for all sections of the corridor, and correlation analysis suggest that these relationships have greatest impact in Hudson Strait.
5. All historical (1950-2013) temperature and salinity profiles over Mackenzie continental slope were examined. The probability of upwelling-favourable wind occurrence is closely linked to the sea level pressure difference between the Beaufort High and the Aleution Low, although the locations of both pressure centers is also of importance.
6. Examination of a 14 year-record of high-resolution and spatially extensive ice thickness observations in the Eastern Canadian Arctic (ECA) identified 12-subregions with distinct sea ice trends. Negative trends in spring ice volume are evident in 9 of 12 regions of the ECA, with interannual variations in spring sea ice volume within the ECA leading to ±20% variations in the volume of freshwater available at the ocean surface during summer.

OBJECTIVES

Our objectives remain the same as was defined in our proposal for this project:

1. Macro-scale – Examine the role of regional to hemispheric scale oceanic and atmospheric forcing (in both space and time) of sea ice dynamic and thermodynamic processes.
2. Micro-scale – Investigate the exchange processes at the micro- to local-scale of mass and energy across the OSA interface with a particular emphasis on high frequency atmospheric and oceanic events and examine the regional variability.
3. Community-Based Monitoring (CBM) – Continue with work linking Western science and Inuit knowledge (IK) through community-based monitoring programs.
4. Technology – Develop quantitative tools to estimate the geophysical and thermodynamic state of the snow/sea ice and make these tools available to our government and industry partners.

KNOWLEDGE MOBILIZATION

Our group has participated in a large number of knowledge mobilization activities. The following lists give a short overview of some of the activities we have participated in.

Throughout the past year our group has presented at 10 national and international conferences and workshops, including:

- IEEE AP-S/URSI 2016 conference, Puerto Rico, July 2016
- Ice Mass Balance Buoy workshop, Alfred Wagner Institute, Bremerhaven, Germany, June 2016
- Seminar Presentation, University of Tromso, April 2016
- Forum for Arctic Modeling & Observational Synthesis, Woods Hole Oceanographic Institute, Massachusetts, November 2016
- Joint Scientific Congress of CMOS and CGU, Fredericton NB, May 2016
- European Geosciences Union General Assembly, Vienna Austria, April 2016
- AGU Fall meeting, San Francisco, December 2016
- ESA Living Planet Symposium, Prague, May 2016
- Manitoba Hydro Day of Learning, Winnipeg, November 2016
- 27 poster and oral presentations at the ArcticNet ASM

As part of our community engagement we have participated in the following meetings that are at a local, provincial, national level, and international level:

- David Barber presented at the Centrallia Global B2B Forum, May 2016, Winnipeg.
- David Barber participated in the SWIPA-AMAP meeting, June 2016, Lund, Sweden.
- David Barber participated at the European Science Open Forum, July 2016, Manchester, UK.
- David Barber hosted the Arctic Institute Meeting, April 2016, Winnipeg.
- David Barber participated in the 'Arctic Live' BBC documentary, November 2016, Churchill.
- David Barber participated at the Exploring the Arctic, February 2017, Michigan State University, Michigan.
- Lauren Candlish, Jonathan Andrews and Zou Zou Kuzyk presented at the Eastern Hudson Bay and James Bay Regional Roundtable meeting, November 2016, Chisasibi.

Students and staff from our group participated in the following Educational Outreach events:

- Science Rendezvous in May 2016, University of Manitoba. Using top research institutions, the annual festival takes science out of the lab and makes its accessible to the public.
- Lauren Candlish and Nathalie Theriault presented and hosted workshops on board the CCGS *Amundsen* as part of the Schools on Board program in September 2016.
- Schools on Board Arctic Climate Change Youth Forum in December 2016. This youth orientated daylong conference is devoted to raising awareness of climate change and ongoing research in Canada's Arctic. The ACCYF is co-hosted with a high school, and aims to bridge Arctic science with science education.
- Annual Schools on Board and Fort Whyte Alive – Arctic Science Day in March 2017. This day gives high school students a chance to learn about Arctic Science from our group and see demonstrations of how to conduct physical sampling of snow and ice in near-Arctic conditions (Winnipeg winter).

David Barber and the Centre for Earth Observation Science are also leading an outreach project called Expedition Churchill. The project is a creative public education and outreach campaign intended to highlight our major research programs and partnered projects operating within the geographic scope of Churchill and Hudson Bay. The project is a partnership with University of Manitoba, Centre for Earth Observation Science, VIA Rail Canada, Town of Churchill, Churchill Northern Studies Centre, Assiniboine Park Zoo - Journey to Churchill, and Travel Manitoba. Our ArcticNet researchers and students are contributing to a multi-media platform, which includes and e-book that will be available on the internet and through the partners of Expedition Churchill. Expedition Churchill is a collaborative project and includes partners University of Manitoba, the Assinaboine Zoo, Churchill Manitoba, and VIA Rail.

INTRODUCTION

In all regions of the Arctic, sea ice regimes are dramatically changing. Recently, Galley et al. (2016) examined the replacement of multiyear sea ice and changes in the open water season duration in the Beaufort Sea. These changes in sea ice are both affected by and have effects on the physical, biological, and meteorological processes operating across the ocean-sea ice-atmosphere (OSA) interface. Campbell et al. (2016) examined the community dynamics of bottom ice-algae in Dease Strait in 2014, highlighting the influence of both light penetration through sea ice and nutrients on algal biomass. Ogi et al. (2016) conducted several studies to investigate the linkages between both local and regional atmospheric circulation patterns and sea ice variability. Dmitrenko et al. (2016) investigated the shelfbreak current of the Beaufort Sea, speculating that wind-driven sea level fluctuations may impact sea ice cover in winter. The changes in sea ice also affects how industry plans and prepares for more accessible marine transportation routes. Andrews et al. (2016) characterized the timing of sea ice on the shipping corridor to the Port of Churchill between 1980 and 2014, indicating significant linear relationships amongst breakup, freeze-up, and the length of the open water season for all sections of the corridor.

As we are more than halfway into this final cycle of ArcticNet, we are continuing to develop our understanding between the dynamic and thermodynamic interactions between the ocean, sea ice and atmosphere. Our goal is to model changes in sea ice based on these interactions and examine the consequences of this change on various ecological and geochemical cycles. Our research takes a systems approach at both local and regional scale studies. Our field campaigns have focused on several different regions of the Arctic: a) the Beaufort Sea, b) Eureka, Nunavut, c) Hudson Bay, d) Cambridge Bay, and e) Greenland. As part of our objectives we look at the regional differences for the processes that are occurring in the Arctic as well as try to replicate these processes with our mesocosm studies at the Sea ice Environmental Research Facility (SERF) in Winnipeg, Manitoba

ACTIVITIES

Our field activities below are listed by field campaign then subdivided into the relevant sub-projects we participated in.

Sea-ice Environmental Research Facility (SERF) -Winnipeg- Winter 2017

Remote Sensing of a Controlled Crude Oil Spill in an Artificially-Grown Young Sea Ice Environment for Detection Purposes - Project led by David Barber and Nariman Firoozy

This project involves the growing of young sea ice in a specifically designed tank within a so-called oil curtain that limits the oil to a pre-defined space. Twenty liters of light crude oil will be introduced from beneath the sea ice into the system when ice has grown to a certain thickness (about 6 cm). The radar signature of the system will be measured continuously through a C-band scatterometer to measure the radar signature changes due to the oil injection, and also as oil moves through the system. Furthermore, a ground penetrating radar (GRP) system at 500 MHz central frequency will be used (a) on the sea ice, and (b) over the sea ice (resembling an aerial GPR system). The data collected through the GPR will be utilized to reconstruct the profile of the oil-contaminated sea ice, and assess the ability of this technology in oil detection. Physical sampling of the oil-contaminated sea ice will allow us to know the true profile at various points of its evolution, better understand the geophysics of the system, and to verify the accuracy of any retrieval methodology for oil detection through the remotely measured data.

Microwave Remote Sensing of frost flowers – Project led by Dustin Isleifson and David Barber with collaborators Nariman Firoozy, Ryan Galley and Jack Landy

A focused study on the C-band polarimetric scattering and physical characteristics of frost-flower-covered sea ice will be conducted at the Sea-ice Environmental Research Facility (SERF). Sea ice will be grown in the outdoor pool. Environmental conditions (air temperature, humidity, wind speed) will be monitored using automated sensors, while seawater and ice temperatures will be monitored through a series of thermocouples installed in the water column. C-band polarimetric scattering measurements will be conducted continuously at a range of incidence angles and surface roughness statistics will obtained at discrete times using a laser scanner system (LiDAR). Physical sampling will take place to characterize the thermodynamic and geophysical state.

The objectives of this study are to 1) describe and quantify the physical characteristics of frost-flower-covered sea ice grown in the SERF pool, 2) to determine the polarimetric scattering characteristics of the frost-flower-covered sea ice, and 3) to examine the link between the sea ice physical properties and the radar measurements.

CCGS *Amundsen* -Canadian Arctic- 2016

Interactions between the Oceanic and Atmospheric Forcing of Sea Ice in the Beaufort Sea - Project led by David Barber and Lauren Candlish

This project was a continuation of the two collaborative industry projects from 2014 to 2015. We continued to look at the interactions between the ocean, sea ice and lower atmosphere. During the campaigns from 2014 to 2015 we deployed 8 of our 11 meteorological towers on the ice. One of these towers survived for a full 12 months. Through the success of previous campaigns we were able to modify the equipment to allow for longer term deployments of two more on ice meteorological towers in the Beaufort Sea. Unfortunately our goal was to deploy the towers on multiyear ice, however due to the conditions we were only able to deploy the towers on medium thick first year ice. These towers are continuing to collect near surface winds, temperature, humidity and pressure. The *in-situ* data will be compared to different forecasted and re-analysis datasets to evaluate the current understanding and ability to correctly forecast or model winds in the high Arctic. In addition this year we also collected radiosonde data during Leg 3 of the *Amundsen* cruise. This data set will supplement the on ice meteorological data and allow for further comparisons of the boundary layer to forecasted and re-analysis datasets.

Oceanic Forcing of Sea Ice in the Beaufort Sea - Project led by David Barber, Lauren Candlish and David Babb with collaboration from University of Washington, Meteorological Service of Canada

During the late summer several types of buoys and ice beacons were deployed in the Beaufort Sea area. These included position only ice beacons, which were designed and built by David Babb and Solara, Polar SVPs provided by the Meteorological Service of Canada.

IceBridge Field Campaign -Eureka, Nunavut- Spring 2016

Environment and Climate Change Canada/National Oceanic and Atmospheric Administration coordinated Operation IceBridge Field Campaign 2016– Collaborative project with ECCC, NOAA, NASA Operation IceBridge, Jack Landy and David Barber

This objective of this project was to examine how snow properties and surface roughness effect snow depth retrievals using the Operation IceBridge University of Kansas FMCW radar. During this campaign there was 8 sites surveyed. At each site 50,000 GPS snow depths were collected, 166 snow water equivalent cores were analyzed, 22 snow pits were measured with snow micro-penetrometer density profiles. Spot measurements were taken for ice thickness, along with over 260 km of GPS EMI ice thickness transects. At each site Lidar measurements were also taken for snow surface roughness.

ASP Field Programs -Station Nord, Greenland- 2016

Sea Ice Geophysics – Ice Mass Balance Buoys – Project led by David Barber and Dave Babb

This project is a continuation of the project led during the 2015 Station Nord Campaign. The purpose of the project is to study the spatial and temporal variability of the landfast ice around Station Nord. Two autonomous ice mass balance buoys were retrieved from the 2015 campaign and re-deployed in conjunction with the ice tethered moorings. These instruments record air, ice, snow and water temperatures, air pressure, surface winds, snow depth and ice thickness for one year. This will reveal the annual cycle and temporal variability of the landfast multiyear ice pack around Station Nord. The spatial variability of ice thickness and snow depth was sampled in conjunction with the CTD transects, during which an Electromagnetic Induction system and a Ground Penetrating Radar system was be towed behind sleds. Repeat sampling of these transects occurred during later legs of the field program to supplement observations of the seasonal melt around Station Nord.

Impact of ocean heat on landfast ice and tidewater glaciers – Collaborative project with Igor Dmintrenko, David Barber, and Sergei Kirrilov

The purpose of this project was to retrieve and redeploy oceanographic moorings from our 2015 campaign. The project started in April 2015 with the major objective to collect oceanographic data and consider the physical mechanisms that potentially impact the landfast sea ice and tidewater glaciers (and vice versa) in the Station North region.

Following the protocols of 2015, the 2016 field campaign included a regional oceanographic CTD survey and the recovery and re-deployment of an Ice Tethered Profiler (ITP) CTD in the vicinity of glacier-ocean contact zone. In addition, ADCP measurements, microstructure turbulence measurements and water sampling below the land-fast ice were executed. The two ice tethered moorings, between the Prinsesse Margrethe Island and Prinsesse Thyra Island, equipped with an ADCP/CTD/ITP were recovered and re-installed near the ice mass balance buoys. In addition, during the 2016 campaign, an autonomous camera was deployed facing the Flade Isblink Glacier, to track calving events in the region.

Community Based monitoring in the Belcher Islands -Hudson Bay– Winter/Spring 2016

Freshwater-Marine Coupling in Hudson Bay – Led by Zou Zou Kuzyk as Collaborative project with Joel Heath and David Barber

This project was successful through the winter 2015 and 2016 programs and was continued into spring 2016. A major goal of this project is to conduct collaborative research activities and develop strong lines of communication with the communities in the Belcher Islands and eastern Hudson Bay/ James Bay. The information gathered is directly related to the Hudson Bay IRIS. Similar to the previous years of the project CTDs transects were done on land fast ice near the community of Sanikiluaq. Master's student Annie Eastwood's was partially funded through this ArcticNet project to participate in the spring field campaign. Annie Eastwood presented initial results from the data collected in this project at ArcticNet ASM 2016.

This project was funded by several projects and is discussed in detail in Dr. Zou Zou Kuzyk's annual ArcticNet report.

ICE-CAMPS Field Campaign - Cambridge Bay–Spring 2016

Enhanced ice algal biomass along a tidal strait in the lower NW Passage of the Canadian Arctic – Project led by CJ Mundy with collaboration from David Barber

The ICE-CAMPS (Ice Covered Ecosystem — Cambridge Bay Process Studies) 2016 field campaign will take place this spring, based on landfast first-year sea ice near Cambridge Bay, Nunavut. The overarching goal of ICE-CAMPS is to investigate physical and biogeochemical processes operating across the ocean-ice-atmosphere interface during the winter-spring-summer transition to improve our understanding of how our warming climate will affect the ice-covered marine ecosystem of the Canadian Arctic. Laura Dalman, a Master's student co-supervised between David Barber and CJ Mundy, particpeated in the spring 2016 field campaign. The aim of her project was to determine how a tidal strait could influence ice algal growth and production. The variables that she collected and analyzed were: current velocities, snow depth, ice thickness, chlorophyll a, particulate organic carbon and nitrogen, nutrients, and taxonomy.

RESULTS

During the past fiscal year (April 2016 – March 2017) we have produced over 35 peer-reviewed publications we have also presented current results at over 20 different national and international conferences and meetings. Due to space restrictions, this section highlights only a small portion of our recent results.

Landfast First-Year Snow-Covered Sea Ice Reconstruction via Electromagnetic Inversion

Firoozy et al (2016) used data collected from the Cambridge Bay field campaign in May 2014 (Figure 1). In this paper, an inversion algorithm was developed to retrieve some geophysical parameters of the snow-covered landfast sea ice in Cambridge Bay. The data utilized in the electromagnetic inversion algorithm are the monostatic normalized radar cross section (NRCS) data of the profile collected by either (i) a C-band scatterometer set up in the region under investigation, and/or (ii) RADARSAT-2 images of the area. The parameters of interest were temperature, density, salinity, and snow grain size. To this end, this remote sensing problem is cast as an inverse scattering problem in which a data misfit cost functional is to be minimized using a differential evolution algorithm. This minimization required repetitive calls to an appropriate electromagnetic forward solver. The utilized electromagnetic forward solver attempted to model both surface and volume scattering components associated with the irradiated rough multilayered medium under investigation.The developed algorithm minimizes the difference between the measured and simulated NRCS data to minimize a misfit cost functional and thus, retrieves the parameters of interest.

Climate change and sea ice: marine shipping access in Hudson Bay and Hudson Strait (1980 – 2014)

Andrews et al (2016) used a passive microwave-based sea ice concentration dataset to characterize the timing of sea ice on the shipping corridor to the Port between 1980 and 2014 (Figure 2). Efforts were made to produce results in a readily accessible format for stakeholders of the shipping industry; for example, open water was defined using a sea ice concentration threshold of ≤15%. Between 1980 and 2014, the average breakup date on the corridor was July 4, the average freeze-up date was November 25, and the average length of the open water season was 145 days. However, each of these three variables exhibited significant long-term trends and spatial variability over the 35-year time period of the satellite instrumental record. Regression analysis revealed significant linear trends towards earlier breakup (-0.66 days per year), later freeze-up (+0.52 days per year), and a longer open water season (+1.14 days per year) along the shipping corridor between 1980 and 2014.

The upwelling of Atlantic Water along the Canadian Beaufort Sea continental slope

The role of wind forcing on the vertical displacement of the -1°C isotherm and 33.8 isohaline depths was examined based on snapshots of historical (1950–2013) temperature and salinity profiles along the Mackenzie continental slope (Beaufort Sea) (Kirillov et al. 2016). It is found that upwelling is correlated with along-slope northeast (T59°) winds during both ice-free and ice-covered conditions, although the wind impact is more efficient during the ice-free season. One of the most important factors responsible for vertical displacements of isopycnals is sustained wind forcing that can last for several weeks and even longer. It accounts for 14%–55% of total variance in isotherm/isohaline depths, although these numbers might be underestimated. The upwelling and downwelling events are discussed in the context of the interplay between two regional centers of action - the Beaufort high and Aleutian low - that control the wind pattern over the southern Beaufort Sea. The probability of upwelling-favorable wind occurrence is closely related to the sea level pressure difference between these two centers, as well as their geographical positions (Figure 3). The combined effect of both centers expressed as the SLP differences is highly correlated (0.68/0.66 for summer/winter) with occurrences of extreme upwelling-favorable northeast winds over the Mackenzie slope, although the Beaufort high plays a more important role. The authors also diagnosed the predominant upwelling-favorable conditions over the Mackenzie slope in the recent decade associated with the summertime amplification of the Beaufort high. The upwelling-favorable NE wind occurrences also demonstrate the significant but low (-0.30) correlation with Arctic Oscillation (AO) during both summer and winter seasons, whereas the high correlation with North Pacific index (NPI; -0.52) is obtained only for the ice-covered period.

Sea ice thickness in the Eastern Canadian Arctic: Hudson Bay Complex & Baffin Bay

Landy et al. (2016) looked at sea ice thickness in the Eastern Canadian Arctic by developing a new algorithm using remote sensing data (Figure 4). Past observations of sea ice thickness in the Eastern Canadian Arctic (ECA) have generally been restricted to drill-hole measurements at a few local sites on landfast ice, limiting the relevance of long-term trend analysis. Here we use data from the laser altimeter ICESat and the radar altimeter Cryosat-2 to present a 14-year record of high-resolution and spatially extensive ice thickness observations for the ECA and identify 12 sub-regions with distinct trends. The mean sea ice growth rate within the seasonally ice-covered ECA from November to April is 235 km^3 mo-1, with the fastest increase in thickness occurring through strong ice convergence and deformation in eastern

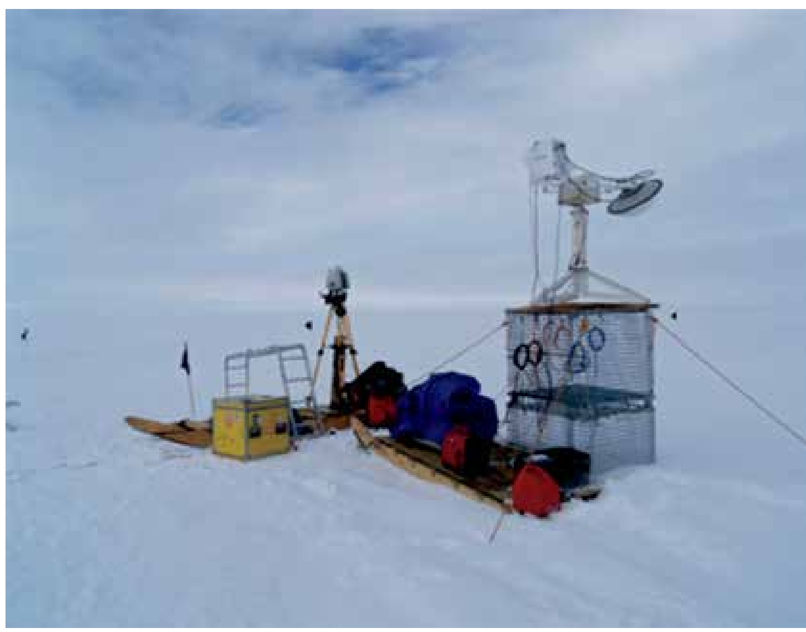

Figure 1. On-site measurements of the scatterometer and lidar from the snow-covered sea ice at Cambridge Bay, Nunavut on May, 2014.

Hudson Bay and Foxe Basin. Negative trends in spring ice volume are evident in 9 of 12 regions of the ECA (and statistically significant in four), although the overall trend of -268 km^3 $decade^{-1}$ (-16 cm ice thickness per decade) is not significant. Our results demonstrate characteristically asymmetrical distributions of sea ice thickness in both Hudson Bay and Baffin Bay, but in opposing directions. In Hudson Bay the spring ice cover is 40 cm thicker in the eastern region compared to the northwestern region, whereas in Baffin Bay the ice is 25 cm thicker in the western half of the bay compared to the eastern half. Although these asymmetries varied over the study period. In Hudson Bay we find that years with strong and positive ice drift vorticity (i.e. cyclonic and convergent conditions) produce increasingly asymmetrical sea ice covers, with the level of west-east asymmetry varying from 2 to 11 cm per 100 km. However, in Baffin Bay the ice drift vorticity is typically negative (i.e. anticyclonic and divergent) with no obvious link to the asymmetry of the spring ice cover. Finally, we estimate that large interannual variations in spring sea ice volume within the ECA lead to ±20% variations in the volume of freshwater available at the ocean surface during summer.

Remote Sensing of Hudson Bay surface salinity

The ocean salinity plays an important role in shaping ocean currents and by controlling the density and the stratification of the water column. In Hudson Bay the salinity is affected every year by the considerable freshwater inputs to the surface layer from both sea ice melt and rivers. Sea ice concentration in Hudson Bay varies from a complete coverage during winter months to completely ice free during summer. In summer, the high input of freshwater from both sources leads to a stronger stratification and a thinner surface layer. Past observations in Hudson Bay shows that the average salinity is around 30 psu, but these are limited to ship cruises and moorings, with restricted temporal and spatial coverage. This can be improved with two recent satellite missions: SMOS products created by the Barcelona Expert Center (available weekly at a resolution of 25 km from 2012-2013) and Aquarius data (available weekly at a resolution of 1 deg from 2011-2014). In this project, surface salinity from

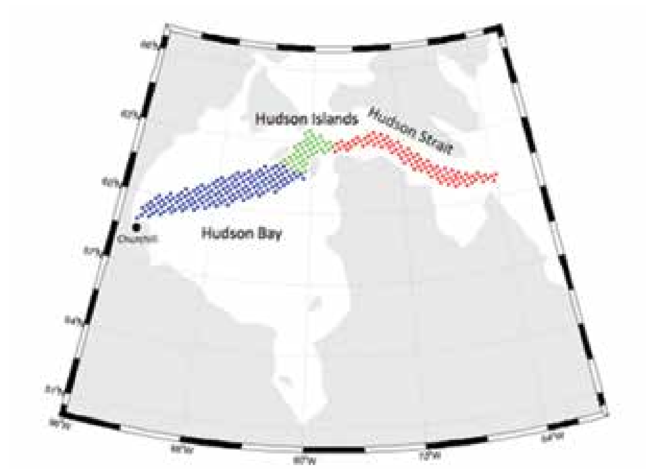

Figure 2. The shipping corridor to the Port of Churchill is indicated with coloured dots; Hudson Bay (blue), Hudson Strait (red), and Hudson Islands (green).

remote sensing was compared to in situ observations (Thériault et al. (in prep)). The spatial and temporal variability of the salinity was also analyzed (Figure 5).

An Assessment of sea ice dynamics in Hudson Bay

This investigation includes an assessment of sea ice dynamics in Hudson Bay in the context of BaySys, a collaborative project between Manitoba Hydro and CEOS designed to determine the relative impacts of climate change and hydroelectric regulation on freshwater-marine coupling in the Hudson Bay complex. Examined in particular is sea ice motion using absolute dispersion statistics relevant for an understanding of distinct dynamical flow regimes (Lukovich et al, 2016).

DISCUSSION

Landfast First-Year Snow-Covered Sea Ice Reconstruction via Electromagnetic Inversion

In this paper, the inversion results were improved by developing an enhanced volume scattering forward solver.

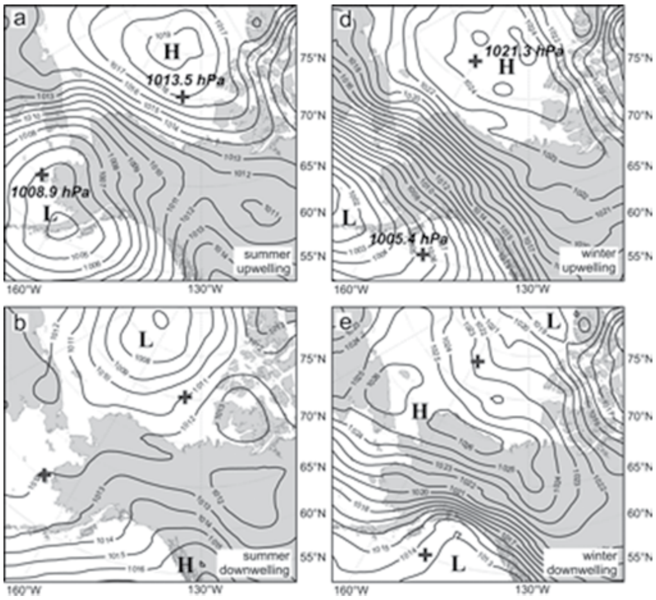

Figure 3. The mean (a,b) summer and (d,e) winter sea level pressure (hPa) for all years with upwelling (a,d) and downwelling (b,e) isotherms and isohalines exceeding ±one standard deviation from mean D-1° and D33.8 over the Mackenzie slope. Black crosses and numbers indicate the 1948-2014 mean Aleutian Low and Beaufort High positions and center SLPs for (c) July-October and (d) March-April.

Therefore, the salinity, temperature, and density profiles were reconstructed with a reasonable accuracy. Among different scenarios investigated, the best results were achieved when both scatterometer and satellite data were utilized in the algorithm simultaneously. The retrieval accuracy will be further improved once the data from satellites with shorter revisit times are employed by the algorithm.

Climate change and sea ice: marine shipping access in Hudson Bay and Hudson Strait (1980 – 2014)

Sea ice timing in the Hudson Strait section of the corridor has diverged from the timing in the Hudson Bay sections. For example, the 2010 – 2014 median length of the open water season was 177 days in Hudson Strait and 153 days in the Hudson Bay sections. Significant linear relationships were observed amongst breakup, freeze-up, and the length of the open water season for all sections of the corridor, and correlation analysis suggest that these relationships have greatest impact in Hudson Strait.

The upwelling of Atlantic Water along the Canadian Beaufort Sea continental slope

The variability in temperature and salinity at intermediate depths over the Mackenzie slope, associated with vertical displacement of the upper boundary of Atlantic Water is large and is correlated significantly with along-slope winds. The linkage between the NE wind and isohalines/isotherms displacement is reasonably high at the synoptic periods of 8-10 days both in summer and winter. The upwelling- and downwelling-favourable winds are controlled by the location and pressure of two major centers of action in atmosphere – the Beaufort High and Aleutian Low. The summertime amplification of the BH is responsible for the predominant upwelling-favourable conditions over the Mackenzie slope in recent decades. The probability of upwelling-favourable wind occurrence is closely linked to the sea level pressure difference between the BH and AL, although the locations of both pressure centers is also of importance.

These results are of interest in the context of the recent warming in the Arctic. Reduction in sea ice extent and thickness, and lengthening of the ice-free season, may cause longer periods with enhanced cross-slope exchange through upwellings and downwellings as suggested by Carmack and Chapman (2003). Moreover, the decrease of sea ice thickness and extent would results in higher sea ice drift velocities (Yang 2009; Spreen et al. 2011) providing more efficient wind energy transfer to the ocean (Martin et al. 2014) and amplifying the Ekman transport. For instance, Williams and Carmack (2015) demonstrated the recent increase of yearly mean upwelling-favourable wind stresses over the open water comparing to that over the ice-covered areas in the Canadian Beaufort Sea. Altogether, it implies that north-easterly winds together with a thinner ice cover may lead to amplified upwelling over the Mackenzie slope during all seasons

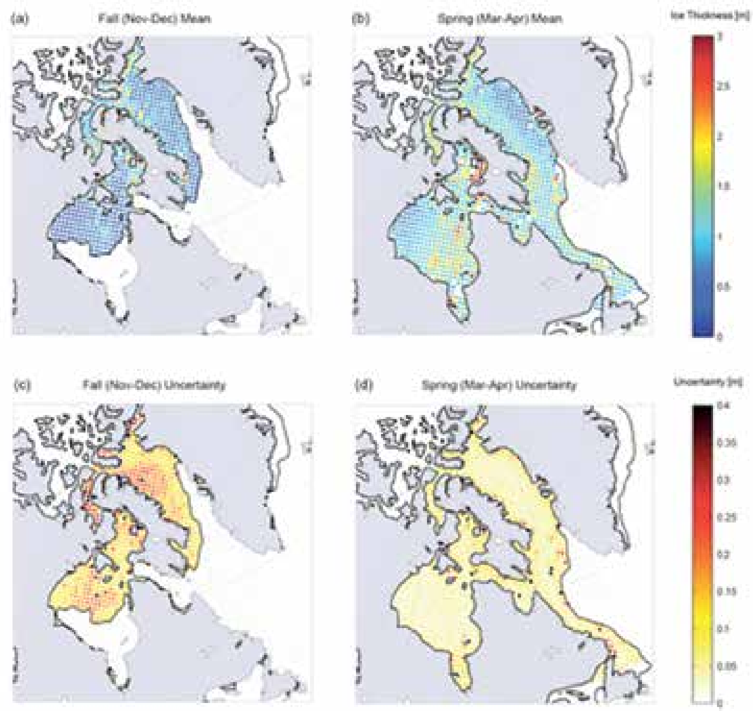

Figure 4. Mean ice thickness and uncertainty for fall (Nov-Dec) and spring (Mar-Apr) across the period 2003-2016.

and increase the availability of nutrients to the euphotic zone within the shelf system and thereby increase biological productivity, particularly in the open water season.

Sea ice thickness in the Eastern Canadian Arctic: Hudson Bay Complex & Baffin Bay

Landy et al. (2016) results suggest that the freshwater yield during summer from melting sea ice would be highest in Foxe Basin (around 1.3 m) and lowest in James Bay, Eastern Baffin Bay and the Labrador Sea (0.3-0.7 m). However, owing to strong interannual variations in spring ice volume, the depth of the freshwater layer at the ocean surface in summer, after all the sea ice has melted, can vary by tens of centimeters. The implication of this variability is that the volume of freshwater within the Eastern Canadian Arctic available for outflow south through the Labrador Sea during summer varies by an estimated ±20% between years.

The prospective launch date for the next major satellite altimeter with a focus on the polar regions is ICESat-2 in 2017. Data from this satellite could be used to extend the sea ice thickness record presented in this study to 15-20 years, which would enable a more robust statistical evaluation of the ice thickness and volume patterns and trends identified here.

Remote Sensing of Hudson Bay surface salinity

In this paper, we will get the first representation of the seasonal and spatial variability of the salinity in the Hudson Bay Complex (Hudson Bay, Hudson Strait, Davis Strait and Baffin Bay). Remote sensing data are compared with *in-situ* data from WOA13 (gathered historical in-situ measurements interpolated at a ¼ deg resolution). Comparison between SMOS data and WOA13 data shows a RMSE of 0.93 psu and a R2 of 0.95. Comparison between Aquarius data and WOA13 shows a RMSE of 1.35 psu and a R2 of 0.84. With larger biases during cold water conditions or when ice is present in surrounding pixels. Averaged surface salinity varies in the order of

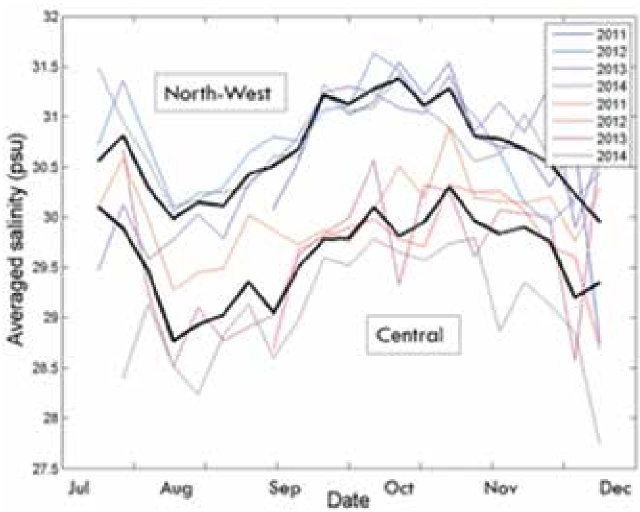

Figure 5. Temporal variability of the ocean surface salinity from Aquarius satellite from 2011 to 2014. Two zones have been averaged spatially: the North-West and Central Hudson Bay (natural delimitation).

1.5 psu from the end of the ice melt to the beginning of the ice formation seasons. With the highest temporal variability in southern Hudson Bay. Due to this high spatial and temporal variability, it is important to obtain more information on the surface salinity of the Hudson Bay Complex. As a next step, comparison between remote sensing data and Nemo simulations will be conducted.

An Assessment of sea ice dynamics in Hudson Bay

Absolute dispersion results show distinct dynamical regimes in Hudson Bay in winter, and interannual variability in dynamical regimes from 2002 – 2012. Northwestern Hudson Bay is characterized by advection; southeastern Hudson Bay is associated with sub-diffusive processes associated with thicker ice in this region. Colours indicate scaling exponent values from absolute dispersion analyses. Results are derived from EXH005 ANHA model output, with high-resolution CGRF atmospheric forcing.

CONCLUSIONS

Our research is continually driven by our desire to improve and expand upon our understanding of the ocean-sea ice-atmospheric interactions and the resultant consequences the changing climate has caused on the biological and biogeochemical processes in the Arctic marine system. This project has been built over the years since the inception of ArcticNet in 2004. The vast scope of this project requires a collaborative approach working with national and international reserachers and organizations. Below is a summary of the contributions from April 2016 to March 2017 to our overall objectives.

1. Macro-scale

   - Galley et al. (2016) examined the replacement of multiyear sea ice and changes in the open water season duration in the Beaufort Sea.
   - Multiple atmospheric circulation related publications were produced by Ogi et al. (2016) including: investigations into Hudson Bay and Arctic Ocean summer sea ice extent and linkages atmospheric circulation; East Atlantic and Northern Hemisphere teleconnections; and variability of temperature and sea ice around Greenland.
   - Lukovich et al (2016) contributed to our understanding of sustainability of the Arctic in a new polar age.
   - We have looked at the Arctic system at a more local to regional scale, examples include: Dmitrenko et al. (2016); Szanyi et al. (2016); Kirillov et al. (2016), Galley et al. (2016).

2. Mirco-scale

   - Our group has investigated the exchange processes at the micro- to local- scale of mass and energy across the OSA interface, examples include: Petrusivich et al. 2017 and Raddatz et al 2016.

- Campbell et al. (2016) investigated community dynamics of bottom-ice algae in Dease Strait.
- In contribution to our micro-scale objective we collaborated with Soren Rysgaard on the SERF project on sea ice geochemistry for mercury ikaite and phosphate.

3. Community-Based Monitoring (CBM)

- We helped support the community-based monitoring project in the Belcher Islands during the 2016/2017 field season.
- Jonathan Andrews, Lauren Candlish, and Zou Zou Kuzyk have compiled community profiles for communities surrounding Hudson Bay and James Bay. This is a contribution to the Hudson Bay IRIS report.

4. Technology

- In contribution towards our technology objective we have developed a technique to detect dielectric properties of artificially grown sea ice (Komarov et al., 2016).
- Publications by Firoozy et al (2016) used microwave remote sensing data to detect the electromagnetic inversion of sea ice and to retrieve sea ice temperature and salinity time series.
- Jack Landy and David Barber participated in the IceBridge Field Campaign in spring 2016 to validate University of Kansas' FMCW radar.
- Our group has also investigated microwave remote sensing of snow covered sea ice, including characteristics such as snow thickness, salinity distribution, melt ponds (Beckers et al. 2017; Casey et al. 2016; Nandan et al 2016; Mahmud et al 2016).

Through our many projects, we have been able to examine the Arctic marine system from a variety of spatio-temporal scales. During the final year of ArcticNet funding we will continue to examine these interacting systems apart of the BaySys project, SERF experiments, and others. During this remaining year we aim to focus on publishing peer-reviewed literature and dedicating time to disseminate our findings to the public via outreach (media, education events, presentations, etc).

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MONITORING MARINE BIODIVERSITY WITH eDNA: A NEW COST-EFFECTIVE METHOD TO TRACK RAPID ARCTIC CHANGES

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ABSTRACT

The ultimate goal of this project is to contribute to coastal sustainable development in the Canadian Arctic by generating new biodiversity monitoring tools and efficiency for informing global shipping-related policies to reduce biological invasions. Marine biodiversity monitoring typically requires expensive sampling tools, multiple experts and may cause significant negative impacts on the ecosystem. The analysis of environmental DNA (eDNA) could be a revolutionary tool to overcome the lack of large-scale standardized biodiversity monitoring. The eDNA method, a novel sampling approach for macro-organisms, detects traces of DNA (i.e., genetic material) in water. This new sophisticated method has the power of identifying local species from only few liters of water, however it has mainly been used in freshwater systems in the south. We therefore aim to optimize the eDNA method for Arctic marine ecosystems to aid in rapidly detecting biodiversity shifts and early detection of introductions of invasive or non-native species. By joining an international multidisciplinary network of molecular, invasion and benthic ecologists and policy makers, the Coastal SEES Collaborative Research Network, we aim to (i) adapt and calibrate the eDNA method for Arctic organisms, (ii) monitor Arctic biodiversity in sensitive Arctic areas, (iii) integrate existing Arctic risk assessments of invasions within global invasion predictive models and (iv) reduce Arctic invasions by integrating an iterative loop of guidance and information between research teams and international shipping policy makers. Because significant global changes are currently underway in the Arctic and shipping is increasing, we believe that creating an eDNA database for Arctic marine biodiversity is pressing. Integrating molecular monitoring methods for Arctic ecosystems is at a perfect time of biotechnology accessibility, biotechnology advances, actual knowledge of marine biodiversity and the access to pristine environments (i.e., before biodiversity shifts have occurred). This study will provide, by means of the most recent biotechnology tools combined with the risk of invasions from coupled changes among global shipping, climate, navigation infrastructure and global trade, concrete results that can be applied towards international management and conservation shipping policies.

KEY MESSAGES

- This project generates a new biodiversity monitoring tool for the marine ecosystem by adapting the so-called “eDNA metagenomics” method for Arctic marine species and potential introduced nonindigenous species (NIS).
- By providing training to local community members and northern research staff, this project provides the foundation for establishing the very first NIS monitoring program in the Canadian Arctic through the development of a community based monitoring (CBM) network/capacity.
- This project is co-funded by many partners, including Polar Knowledge Canada, Fisheries and Oceans Canada (Aquatic Invasive Species Monitoring Program, Ocean and Freshwater Science Contribution Program (OFSC), and Strategic Program for Ecosystem Research and Assessment), the Nunavut Wildlife Management Board and the Nunavik Marine Region Wildlife Board which allows performing large-scale eDNA monitoring that will document spatio-temporal eDNA variation throughout the Arctic ecosystem.
- A baseline description of Arctic community composition and DNA sequences is now available to track long-term Arctic coastal biodiversity shifts in sensitive coastal areas (Churchill, Iqaluit, Deception Bay, Pond Inlet and Milne Inlet).
- For the first time, we successfully used eDNA metabarcoding of water samples to characterize coastal metazoan species in the Arctic (i.e., in contrast to year 2015-2016 where we only tested

the efficiency of metabarcoding *in silico* and *in vitro*).

- We show that eDNA is spatially and temporally heterogeneous within ports and that the efficiency of the eDNA monitoring surveillance is improved when sampling under-ice cover. Our results demonstrate that the analysis of eDNA from Arctic water samples could be a revolutionary tool to increase the power of detection, spatial coverage and frequency of sampling, thus improving detection of biodiversity shifts in large coastal Arctic ecosystems.
- Because recent studies suggested that marine sediments have greater magnitude of eDNA concentration than seawater, and that ancient and extant communities can be ascertained, we have extended this eDNA water column project to testing eDNA also collected in sediment samples.
- By developing a new collaboration at McGill University (Dr. Melania Cristescu), we are also comparing the efficacy of metabarcoding with various sampling methods (bulk plankton collections versus eDNA in water) across varying spatial and temporal gradients.
- Based on our international collaboration *Coastal SEES Collaborative Research Network* (NSF funding), our results support the view that eDNA metabarcoding has the potential to facilitate aquatic biodiversity surveys worldwide, to predict Arctic invasion risk (i.e. port connectivity in ports) and a list of recommendations for port eDNA metabarcode surveys was developed.

OBJECTIVES

We are pursuing the objectives identified in 2014, at the start of our ArcticNet Phase IV project. This list of objectives comprise those of the last two years as there is obviously some overlap between them to ensure the continuity of the research that we originally proposed.

1. Optimize the effectiveness of the eDNA sequencing approach to capture the broadest metazoan Arctic biodiversity from water samples by:

- Continuing to compile a species list reference database of Arctic species and potential aquatic invasive species (AIS)/nonindigenous species (NIS); and
- Developing a library of Arctic DNA sequences.

2. Detecting Marine Biodiversity Shifts in ports with substantial shipping activity by:

- Optimizing water sampling strategies for eDNA in Arctic marine environments;
- Using the primers developed and tested in Goal 1 to estimate metazoan diversity; and
- Increasing the accuracy of biodiversity monitoring in the Arctic using eDNA for improving the evaluation of impacts from climate change and long-term human activities in the coastal Canadian Arctic.

3. Navigation in the Changing Arctic and Consequences for Marine Invasions

An eDNA standardized approach to biodiversity monitoring could allow testing and calibrating global predictive NIS models and inform international policy makers about Arctic coastal invasion risk. We thus explored the potential for metabarcoding of environmental DNA (eDNA) to provide an easier and taxonomically broader survey method for metazoans (multicellular animals) in commercial ports across the world by;

- Investigating the performance of two published primer sets that amplify different sequences across a wide-range of metazoans (multicellular animals) at the global scale (i.e. also on potential Canadian Arctic invaders detected in international ports), the mitochondrial COI gene and the nuclear 18S gene;

- Examining variation in eDNA sampling and sequencing effort at different spatial scales from these datasets in various environmental conditions; and
- Testing two approaches to estimate global biodiversity patterns (1) the data to the lowest observed read or sample number, or 2) use biodiversity metrics that are robust to unequal sampling efforts.

4. Establishment of a community based monitoring (CBM) network/capacity by:

- Providing training to local community members and northern research staff in user-friendly port survey collection methods and eDNA sampling techniques.

KNOWLEDGE MOBILIZATION

- Oral presentations for *Coastal SEES Collaborative Research: Changes in ship-borne invasions in coupled natural-human systems: infrastructure, global trade, climate and policy* (University of Notre Dame: July 2015, February 2016; Cornell University in New York: June 2016; Governors State University in Chicago: July 2017)
- Radio-Canada (La Semaine Verte; November 2016, summer 2017: http://ici.radio-canada.ca/tele/la-semaine-verte/2016-2017/segments/reportage/10866/eau-adn-poissons)
- *Guide to the identification of non-indigenous marine species with potential for introduction to the Canadian Arctic* (distributed to various northern communities and organizations, November 2015, January 2017)
- *CAISN annual meeting*: Halifax (Nova Scotia; invited in May 2015), Windsor (ON; Oral presentation in May 2016)
- 12th ArcticNet Scientific Meeting (ASM2016), Winnipeg (MB); December 2016. Oral presentation by Kimberley Howland and poster presentation by Noémie Leduc)
- Québec-Océan, oral presentation at Rimouski (Qc); November 2016
- Cégep de Ste-Foy (Qc), oral presentation; September 2016
- Invited oral presentation at ICES Working Group on Ballast and other Shipping Vectors Meeting (Olbia, Italy, March 2016)
- Oral presentations at Baffinland Marine Environment Working Group Meeting (April and November 2016)
- Ikaarvik 1 day workshop with youth, meetings with Mittimatilik Hunters and Trappers Organization, and Pond Inlet Hamlet Council in Pond Inlet, NU (January 2017)
- Pond Inlet radio station - presentation and question and answer period in Pond Inlet (January 2017)

INTRODUCTION

In the Arctic, climate change and marine invasions are expected to result in high species turnover of over 60% of the present biodiversity with substantial ecological disturbances of marine ecosystems[1]. Climate change is also expected to open new waterways in the Arctic Ocean, resulting in greater shipping traffic[2-5]. Predicted increases in shipping frequency and routes[6], increased infrastructure development in ports, and associated chemical and biological pollution will place other ecosystem services at risk. The introduction of undesirable NIS may displace native species, alter community structure and increase fouling of fishing gear, particularly in estuaries and coastal zones[7,8]. The impact of NIS on industry and society often lead to long-term economic consequences; in Canada, high impact NIS directly and indirectly amount to costs between $13.3 and $34.5 billion/year[9-11]. Monitoring large-scale and continuous biodiversity in the Arctic is therefore essential for effective management and conservation plans and ensuring ecosystem sustainability[12]. However, heavy and expensive sampling tools (e.g., bottom trawl) are often required and a large pool of expert taxonomists is necessary for follow-up identification of organisms; limiting the capacity of monitoring marine species at large spatial and temporal scales in remote regions. Indeed, many areas of the marine Canadian Arctic and their fauna are still poorly known[13], preventing a large-scale ecosystem assessment.

The analysis of environmental DNA (eDNA) could be a revolutionary tool for overcoming the lack of extensive species distribution data[14]. The eDNA method allows the detection of traces of DNA from macro-organisms in cellular or extracellular form in water[15]. The popularity of this method is growing so fast that species inventories collected via eDNA in water samples could soon surpass species detection from traditional sampling methods[16-19]. Thus, the ease of harvesting water samples could allow rapid sample collection, reduce the cost associated with data collection and does not require the manipulation of organisms[14,20]. eDNA metabarcoding (i.e. high-throughput eDNA sequencing) may allow the simultaneous identification of several million DNA fragments in a given water sample, providing a powerful tool to screen the aquatic biodiversity in habitats that have not yet been surveyed due to limited resources.

The potential of false positive and negative results due to technical artifacts during the bioinformatics and the lack of knowledge of the local genetic diversity still impose some limitations to the full integration of eDNA metabarcoding within management framework and requires therefore an evaluation of the efficiency of the method. Moreover, most eDNA metabarcoding based on water samples has been done in freshwater environments. Therefore, we still know little about the efficacy of eDNA metabarcoding in surveying spatial and temporal variation in marine coastal biodiversity[21,22]. Improving knowledge about how eDNA community structure spatially and temporally vary is thus particularly important to optimize the assessment of biodiversity and detecting biodiversity shifts.

ACTIVITIES

We have analyzed a higher number of samples per port than expected in the initial proposal and in the 2016 report (N_{total} = 378 samples already sequenced, e.g. Churchill: 60 samples expected vs 177 samples). In addition to having optimized the eDNA method, we have included the analysis of sediment eDNA (in addition to eDNA within the water column) and compare the efficacy between eDNA to DNA sequencing of bulk zooplankton samples. We have also developed new national collaborations (Melania Cristescu at McGill, Cathryn Abbott and Kristi Miller-Saunders at DFO, Eric Solomon Director of Arctic Programs at Vancouver Aquarium, Jackie Dawson at University of Ottawa) and we are continuing to develop a community based eDNA monitoring network. ArcticNet funding allows us to sample the port of Churchill, while our additional funding also allows us to sample Iqaluit, Deception Bay, Milne Inlet and Pond Inlet. In addition, our international collaborations have also enabled us to compare the eDNA biodiversity of Arctic ports with other international commercial ports (Singapor, Chicago and Adelaide) in order to calibrate predictive invasion risk models.

Goal 1. Optimize the effectiveness of the eDNA sequencing approach

In situ

- Methodologies commonly used for concentrating eDNA from water samples on filters composed of different materials (Cellulose Nitrate (CN) and Glass Fiber (GF)) of varying pore sizes (0.45 µm

– 1.2 µm) were tested. Additionally, we tested how different extraction methods interact with filter type and pore size on total extracted eDNA and whether this is correlated with differences in biodiversity detected from water samples.

- A bio-informatic pipeline freely available on the Github long-term software hosting site (www.github.com/edna_pipeline; the present analyses were run using version v0.9) has been developed for the COI region to determine the sequences at the species level. Direct taxonomic assignment of each read without pre-clustering was applied to avoid clustering (i.e. Operational taxonomic units (OTU) clustering) different species with low interspecific divergence.
- Reads matching for more than one species with equal quality scores due to low interspecific divergence were determined using Usearch. For each case, the list of species was scrutinized and species that were clearly not expected in the Arctic (i.e., not previously observed and unable to survive there based on known distribution) based on OBIS, The World Porifera Database, the WoRMS database and expert knowledge were removed from the sequence reference database mentioned above.

Goal 2. Marine biodiversity shift in Arctic ports

Spatial variation

- Churchill (summer 2015-2016), Iqaluit (summer 2015) and Deception Bay (summer 2016): samples collected from 13 sites at three different depths and 12 tide pools.
- All samples extracted and amplified.
- Extraction and Illumina MiSeq done for all port surveys; Churchill (August 2015), Iqaluit (August and November 2015), Deception Bay (August 2016).
- Species databases pooled to evaluate the eDNA efficacy compared to local knowledge.
- Data analyzed for location comparison (i.e. depth and tide pools).
- M.Sc. graduate student, Noémie Leduc (U. Laval): comparison of Alpha, Beta and Gamma diversity indices between the eDNA and taxonomic data to improve our knowledge about local eDNA dispersal and the variability in eDNA efficiency between different taxa.

Temporal variation

- Annual in Churchill (summer 2015-2016).
- Tidal variability in Churchill (3 sites X 2 depths (surface and deep (~50 cm from the bottom)) X 3 tides (low, high and mid-tide (between low and high tide)) X 3 consecutive days).
- Seasonal variability (with and without ice cover) in Iqaluit (summer and fall 2015), Churchill (summer and fall 2017) and Pond Inlet (summer and fall 2017).
- All samples extracted and amplified.
- Illumina MiSeq done for Churchill (summer 2015 and 2016), Iqaluit (summer and fall 2015) and Deception Bay 2016.
- Data analyzed for the seasonal variation (fall 2017).

SedDNA metabarcoding

Recent studies showed that marine sediment eDNA concentrations may have three orders of magnitude higher eDNA than seawater eDNA (Torti et al. 2015). Moreover, in sediment, eDNA ancient and extant communities can be ascertained (Lejzerowicz et al. 2013). Therefore, because use of sediments may significantly increase biomonitoring from eDNA in Arctic coastal ecosystems, we also collected eDNA from sediment samples (sedDNA). This project was made feasible due to additional POLAR funding ($15k over original funded amount).

- Churchill and Deception Bay (2016): 3 beaches X 4 tide pools X 5 replicates.
- Two sedDNA extraction methods were compared -a classical sedDNA extraction method

(PowerWater ® DNA Isolation Kit MoBio) vs. a new cost-effective method (E.Z.N.A Genomic DNA Isolation Kits OMEGA Bio-Tek): extraction (both methods), amplification, visualized efficacy on agarose gel electrophoresis and Illumina MiSeq sequencing have been completed.

Bulk plankton metabarcoding

Recent studies also showed the efficiency of the metabarcoding of bulk zooplankton samples to monitor large-scale coastal environments (Chain et al. 2016). To improve port survey and standardize sampling to assess biodiversity and detect invasive species from coastal marine environments in the Arctic, we are thus comparing efficacy of metabarcoding with various sampling methods (bulk plankton collections and eDNA in water) across varying spatial and temporal gradients.

- Thanks to POLAR funding, we have been able to conduct vertical plankton tows with an 80 µm net by lowering the net to approximately 1-2 m from the bottom: 13 sites each in Churchill (summer 2015), Iqaluit (summer 2015) and Deception Bay (summer 2016). We can now use those zooplankton samples for this project thanks to extra funding through our collaborators (McGill $15k and POLAR $10k).
- Churchill and Iqaluit samples are extracted, amplified and Illumina MiSeq sequenced.

Goal 3. Estimating patterns of global biodiversity with eDNA metabarcoding

Our current knowledge of ship-born invasions is limited by incomplete information on species distributions in many parts of the world and how they are responding to changes in climate and shipping traffic. Here we explore the potential for metabarcoding of environmental DNA (eDNA) to provide an easier and taxonomically broader survey method for metazoans (multicellular animals) in commercial ports across the world. International ports funded and surveyed by the *Coastal SEES Collaborative Research Network*.

- In Churchill, Iqaluit and Deception Bay, 20 samples were taken at one site on August 2015 and 2016 from a dock. At the Port of Chicago, 20 samples were taken at one site on November 20th, 2013 from a dock. In Singapore, a total of 40 samples were taken across two sites on July 11th, 2014 from docks (n=20 per site). In Adelaide, a total of 66 samples were taken across seven sites on July 3, 2014 from a boat, with four sites sampled within 2 m of a dock and three sites sampled in the middle of the channel perpendicular to a dock site (n=9 or 10 per site).
- Investigated the performance of two published primer sets that amplify different sequences across a wide-range of metazoans (multi-cellular animals), the mitochondrial COI gene and the nuclear 18S gene.
- Examined variation in eDNA sampling and sequencing effort at different spatial scales from these datasets.
- Demonstrate two approaches to estimate global biodiversity patterns when sampling or sequencing effort varies.

Goal 4. Community based monitoring network

Training of local community members and permanently stationed northern research staff in basic port survey collection methods and eDNA sampling techniques was also conducted annually in summers 2016 in conjunction with sample collections at high risk port sites.

- Hands on sampling and data collection with trained researchers using zooplankton nets, Niskin samplers, water sampling for water quality and eDNA, and boat/beach-based sampling for benthic/fouling organisms using cores, grabs and a trawl (Churchill 2015-2016, Iqaluit 2015-2016, Salluit-Deception Bay 2016).

- Local boats and guides hired in each community (Churchill 2015-2016, Iqaluit 2015-2016, Salluit-Deception Bay 2016).
- Training workshops (on eDNA and basic information on invasion biology, invasion risks in Arctic marine environment) with Ikaarvik (Arctic Inspiration Prize Winners) youth in Pond Inlet as well as with HTO members in four communities (2015-2017).
- Tissue sample kits, identification booklets with descriptions of high risk non-indigenous species and plain language project descriptions/updates provided to each community for future use (Kangiqsujuaq, Kuujuak, Igloolik, Hall Beach, Iqaluit, Pond Inlet; 2015-2017).

RESULTS

As described in the original project, the year 2015-2016 was devoted to the development of the eDNA methodology for Arctic coastal ecosystems (i.e. goal 1 of the original research proposal), whereas the year 2016-2017 was devoted to to analyzing Arctic *in situ* data. We thus put these technological developments into practice to analyze eDNA collected in Arctic ports. In addition to the successful biomonitoring from eDNA, our results revealed variation in spatio-temporal eDNA composition. We have therefore initiated the study of eDNA ecology in the Arctic coastal environment. We also provide a list of recommendations for port eDNA metabarcode surveys. The analysis of the in situ eDNA data was originally planned for the fall of 2017 and the project's progress is thus far ahead of the initial milestones.

Goal 1

We found a significant effect of filter type (CN vs. GF), pore size, and extraction method on detection of biodiversity from eDNA (Figure 1). Specifically, the combination of CN filters of a pore size greater than 0.7 μm combined with a phenol-chloroform-isoamyl alcohol extraction recovered a higher amount of total DNA from the same volume of water compared to other filter types, pore sizes and extraction methods tested. Furthermore, this difference in total DNA extracted resulted in two or three times the number of Operational Taxon Units (OTUs) being detected compared with other combinations. We therefore recommend using cellulose nitrate filters with pore sizes greater than 0.7 μm to be used when concentrating eDNA from water samples in shipping ports and that careful consideration of extraction methods and their DNA yield is warranted because these choices can bias the amount of biodiversity detected from an environmental sample.

We obtained a total 712,494 aquatic eukaryotic reads in Churchill (200,732 reads for COI1 and 511,762 reads for COI2) and 178,728 aquatic eukaryotic reads in Iqaluit (100,139 reads for COI1 and 78,589 reads for COI2). For both ports, the sequencing depth could have been increased (within-sample read rarefaction curves did not reach the saturation for most of the samples). Sample accumulation curves also showed that some of the locations were under-sampled (specifically the Surface, Mid, and Deep locations at each site) however there was little evidence for spatial eDNA aggregation within a location as sample-based curves fell only slightly below read curves at all locations (Figure 2).

Optimized methods are now being utilized in further studies such as collection of shore-based eDNA to characterize native and introduced biodiversity across ca. One hundred sites along Canada's three coasts through the Students on Ice C3 expedition.

Goal 2

A total of 181 species was detected, including 140 species in Churchill and 87 species in Iqaluit (Figure 3). A total of 48 species was amplified with both COI primer sets, 116 species recorded by the COI1 primer set only and 17 species by the COI2 primer set. The primer sets detected a total of 10 phyla, including nine phyla for the COI1 primer set (44 Annelida species, 31 Arthropoda, 35 Chordata, 17 Cnidaria, 17 Echinodermata, eight Mollusca, three Nemertea, five Porifera and 4 Rotifera) and 10 for the COI2 primer set (27 Annelida species, 10 Arthropoda, two Bryozoa, five Chordata, 6 Cnidaria, one Echinodermata, eight Mollusca, two Nemertea, three Porifera and one Rotifera).

For both sampled ports, the congruence between meta-barcoding and historical Arctic data was 74.0% (Churchill: 70.0% and Iqaluit: 87.4%; COI1: 78.6% and COI2: 61.5%). A total of 47 species were detected which represents 15 Annelida, five Arthropoda species, two Bryozoa, four Chordata, eight Cnidaria, two Echinodermata, four Mollusca, three Nemertea and four Rotifera taxa) (Figure 4). The 'absent' species may be new Arctic species records, unexpected invaders or closely related non-Arctic species due to the fact that local Arctic species are not yet represented in the sequence reference databases. On the other hand, species that are not detected may depict a non-amplification by any of the primer sets, a low eDNA release in the water column (organic matter not released or not captured) or the need to capture the local intra- and interspecific variability by sequencing a greater number of specimens. One of the new Arthropoda species, *Acartia tonsa* detected with the COI1 primers in Churchill (64 reads averaging 99.4% similarity with the sequence references) was previously recorded in ballast water in connected Churchill ports and is considered a potential invader. However, the sequences in BOLD of A. tonsa were not monophyletic and some sequences between *A. tonsa* and the native *A. hudsonica* were identical in Genbank. Therefore, a misidentification of the organism is most likely.

Spatial eDNA distribution

For both ports, the community structure changed significantly between the water column and the tide pools, but the explained variance was greater for Churchill than Iqaluit (Figure 5, PERMANOVA; Churchill: $R^2 = 0.21$, $P < 0.001$; Iqaluit: $R^2 = 0.12$, $P < 0.001$). For both ports, the water column was

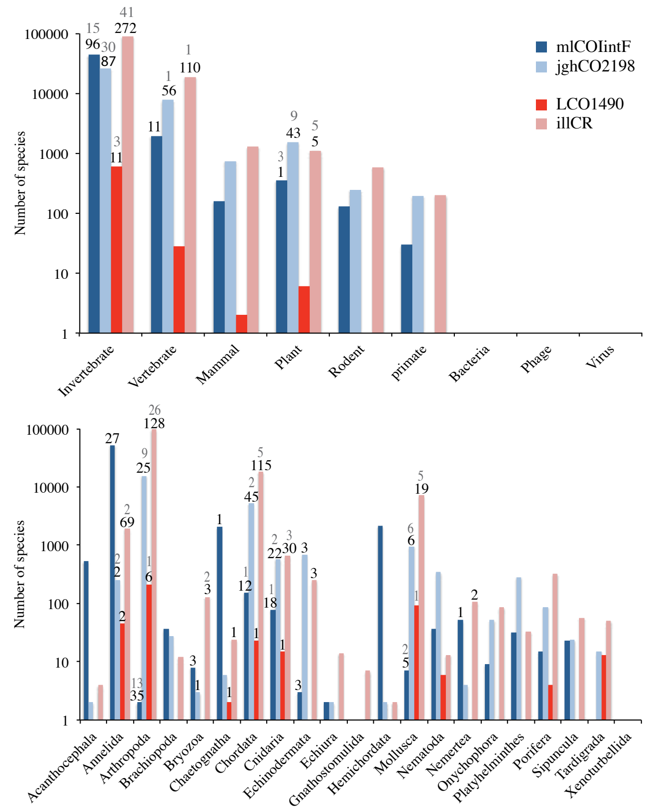


Figure 1. Mean PCR 2 DNA concentrations (indexed libraries) (y-axis) for each set of explanatory variables including extraction type (A), filter pore size (B) and filter type (C). Extraction types include chloroform (Cl), phenol chloroform 1 (PCl 1) and phenol chloroform 2 (PCl 2) extractions. Filter types included cellulose nitrate (CN) and glass fiber (GF). The upper and lower whiskers correspond to the 1.5 times interquartile range.

dominated by Arthropoda, followed by Annelida and Rotifera species were detected in the water column but not in tide pools. In Iqaluit, the tide pools had an estimated Sørenson similarity index of 0.65, 0.64, 0.62 with the surface, mid-depth and deep water respectively, whereas in Churchill the tide pools had estimates of 0.67, 0.84, and 0.68 with the surface, mid-depth and deep water respectively. In Churchill, despite a greater number of reads in tide pools than water column (averaging 23,276 and 11,623 reads in tide pools and water column samples respectively;

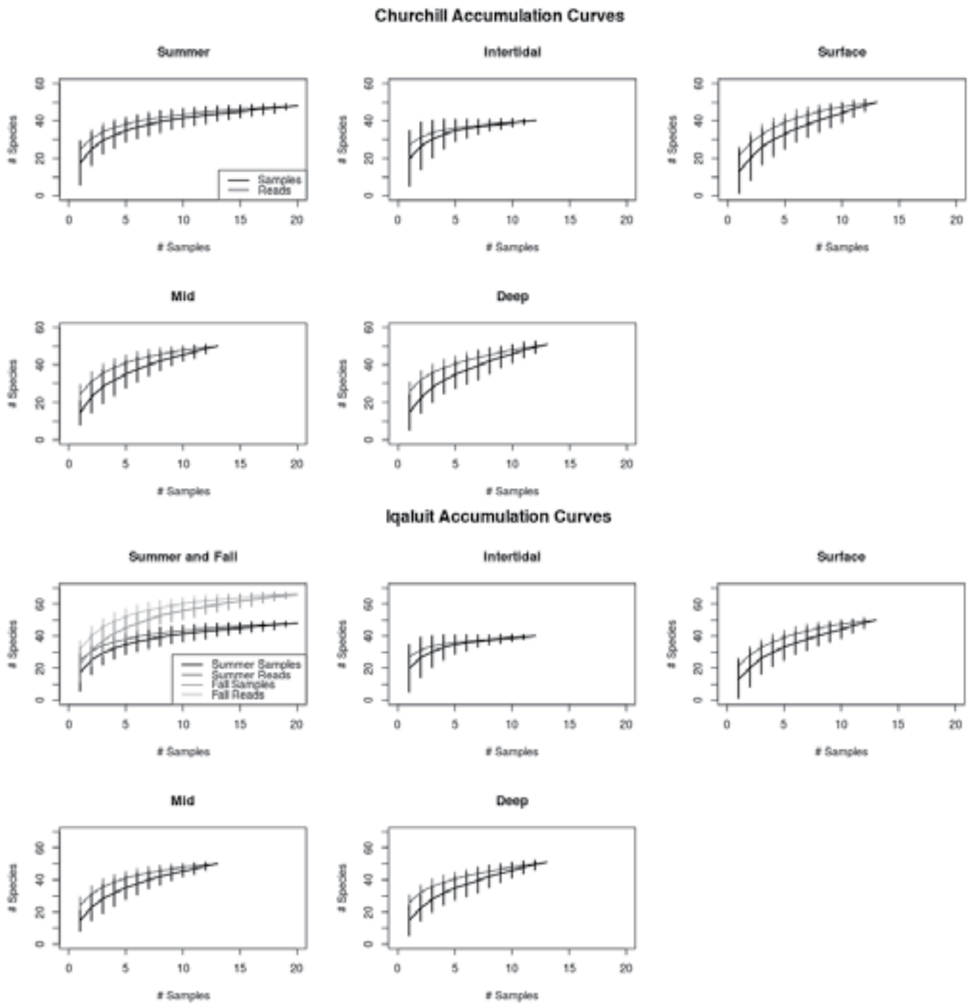


Figure 2. Rarified species accumulation curves by read and sample numbers for each site for Churchill (top) and Iqaluit (bottom). Solid bold line denotes COI read rarefaction and light line denotes COI sample rarefaction. Errors bars represent 95% confidence intervals.

ANOVA: $P = 0.06$), there was no significant difference in species richness between samples collected in the water column and tide pools (averaging 25.40 and 30.27 species in tide pools and water column samples respectively; ANOVA: 0.42; Figure 6). In contrast, in Iqaluit, despite the similar number of reads in the tide pool and water column samples (averaging 1,061 and 1,716 reads in tide pools and water column samples respectively; ANOVA: $P = 0.50$), species richness was significantly higher in tide pools than water column (averaging 18.33 and 13.92 species in tide pool and water column samples respectively; ANOVA: $P = 0.02$). In both ports, Mollusca species were mostly detected in tide pools relative to the water column (Figure 7a,b). In Churchill, the tide pools were dominated by Mollusca (95.8% (i.e. 14,219 reads) and 100% (i.e. 198,684 reads) of Mollusca reads were *Littorina saxatilis* for COI1 and COI2 respectively). However, in Iqaluit, tide pools were dominated by Arthropoda species.

The community structure differed significantly among the water depths (Figure 5, Churchill: R^2 =

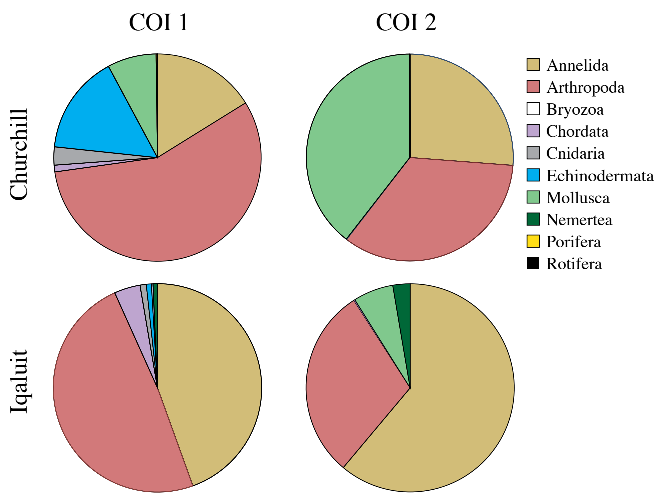


Figure 3. The proportion of phyla detected in Churchill and Iqaluit from the COI1 (mlCOIintF-jgHCO2198) and COI2 (LCO1490-ill_C_R) primer sets separately.

0.13, P < 0.001; Iqaluit: R^2 = 0.08, P = 0.04), but the proportion of explained variance was greater for Churchill than Iqaluit. The Arthropod *Balanus balanus* dominated the deep water of both ports and *Nemertae* was found only in mid-depth in Iqaluit (Figure 7b). In Iqaluit, the species richness did not differ significantly among the depth layers (ANOVA species richness: P = 0.3). In Churchill, higher species richness was found at the surface (ANOVA: P = 0.02), which generally corresponded to where there were more freshwater inputs from the Churchill River (Figure 8).

Seasonal variation

The community structure largely varied between seasons (Figure 5, PERMANOVA; R^2 = 0.30, P < 0.001); Arthropoda dominated the summer samples whereas the Annelida dominated in fall (Figure 7; S20 and F20 samples shared 54.1% species). Both reads abundance and species richness were greater under ice cover than summer (reads abundance: t = 4.8, P < 0.001, df = 38.0; richness: t = 2.3, P = 0.02). There was 9.03 times more reads in fall than summer (F20: 89,066 total reads, averaging 4,453.3 read per sample; S20: 9,860 total reads, averaging 493.0 reads per sample) and species richness averaging 21 and 17 species in fall and summer samples, respectively (Figure 6).

Goal 3

On average, the COI samples plateaued at a higher read number than did the 18S samples. Sample accumulation curves revealed that aggregation of MOTUs within samples was apparent at all sites for both primer datasets, as sample curves all lay below their read curves (Figure 9). This aggregation, typically attributed to spatial aggregation of species in traditional surveys, could here be due to either spatial aggregation of eDNA in port surface waters or variation in PCR reactions among samples. Churchill had relatively higher than expected MOTU richness estimates, ranking first and second in the rarified and un-rarified COI datasets respectively. This highlights the influence of sampling method on biodiversity metrics, and also suggests that the combination of filter type, extraction method, and library preparation was better for the Churchill samples. Churchill also shared a significantly higher proportion of species with Chicago (Figure 10).

Goal 4

In addition to Y1 community trainings, an introduction to invasion biology and eDNA training workshops were conducted with Nunavut Arctic College students in Iqaluit and Pond Inlet as well as with HTO and community members in Pond Inlet, Igloolik, Hall Beach and Kangiqsujuak (November 2015 and January 2017) and with a group of Ikaarvik youth in Pond Inlet (January 2017). In Iqaluit, training was provided to local community members (five people in 2015, three people in 2016) as well as research staff (training fishery officer stationed in Iqaluit, and a summer student who is a Nunavummiut resident of Iqaluit and pursuing a university degree in marine biology). In addition to training workshops, we have conducted outreach through TV program (Radio-Canada, La Semaine Verte; November 2016, summer 2017: http://ici.radio-canada.ca/tele/la-semaine-verte/2016-2017/segments/reportage/10866/

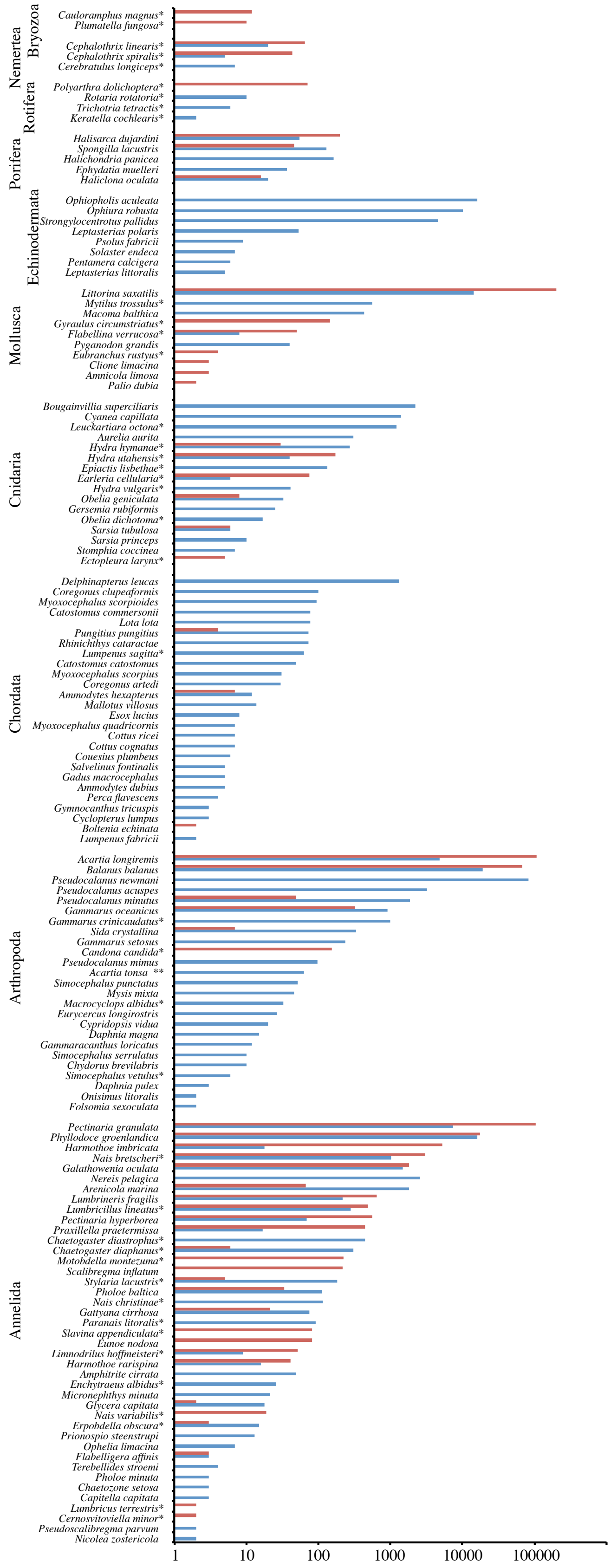
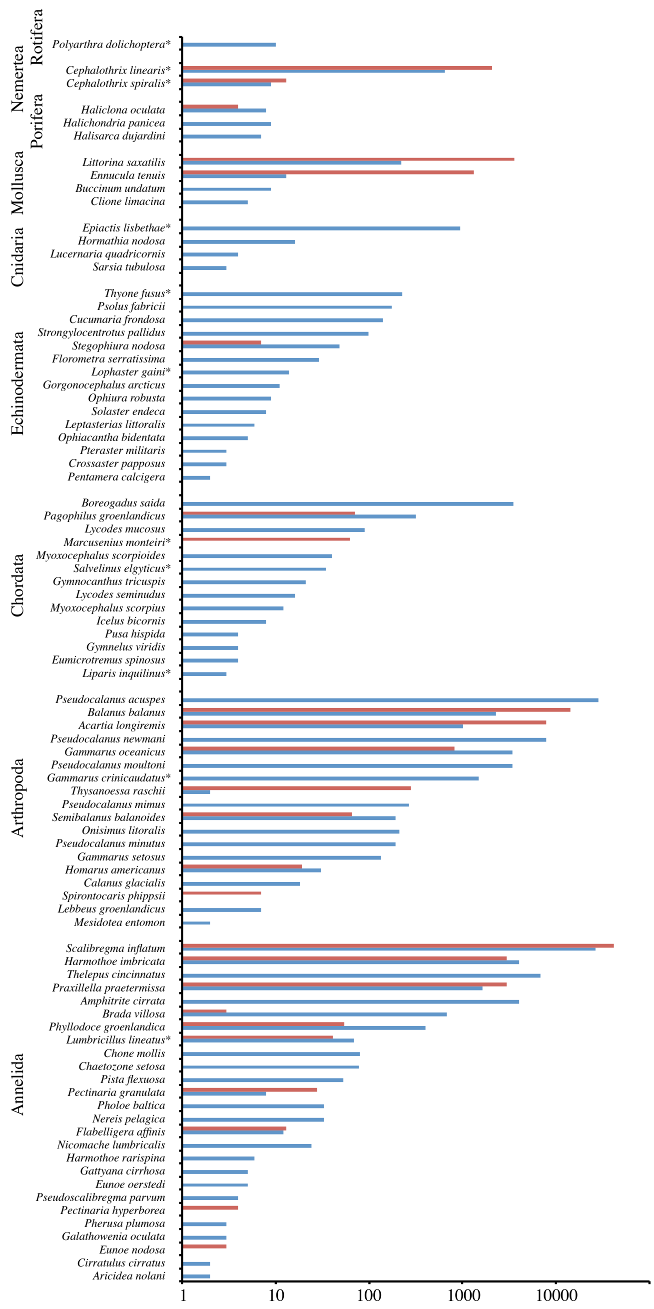


*Figure 4. Species list and their relative actual status within previous Canadian Arctic reports for each primers and port separately. The number of reads for each species detected from the eDNA (COI1 in blue and COI2 in red) collected in Churchill (left) and Iqaluit (right) in 2015. * depict that this species was previously detected in the Arctic and ** is a potential invader.*



eau-adn-poissons) radio shows (local radio show in Pond Inlet, January 2017) and interactive exhibits for the general public (Pond Inlet Co-op January 2017). Sampling devices, and example specimens of invasive and similar native species were brought to workshops and meetings; participants were allowed to handle these and shown how to distinguish them. New additional funding (DFO OFSC: $80k) has been obtained to pursue eDNA trainings in summer 2017 and community-based seasonal sample collection in summer-fall 2017.

DISCUSSION

The development of improved targeted biodiversity monitoring programs is particularly crucial in order to maintain the integrity of Arctic coastal marine ecosystems. Our general objective is to adapt eDNA analysis to Arctic marine ecosystems for detection of spatio-temporal biodiversity shifts. Our results show that the database generated here offers great potential to build a benthic and fish biodiversity DNA database in Arctic ports and DNA sequences, which will provide a baseline for rapid detection of Arctic coastal biodiversity shifts (i.e., native species loss/declines, NIS introductions/range expansions). The 74% congruence between historical Arctic data and eDNA samples confirms the efficacy of eDNA metabarcoding collected by water samples to evaluate the Arctic coastal communities at the species level. In the Canadian coastal Arctic, 30–40% new benthic species are detected each time when site is surveyed using traditional methods. It is therefore not surprising that the congruence between the species detected here by metabarcoding and the historical data may not be higher than what we find. Moreover, groups such as Bryozoans, Nemerteans and Rotifera are currently not included in the historical Arctic Canada records and maybe good indicators for assessing biodiversity shift due to ice cover changes. The eDNA metabarcoding method might thus be the only practical approach to evaluate the community changes of many such species groups. Together, the identification at the species level, the local habitat variability and the effectiveness of the eDNA method under ice cover, is likely to make eDNA metabarcoding a very efficient complementary tool to detect Arctic coastal biodiversity changes.

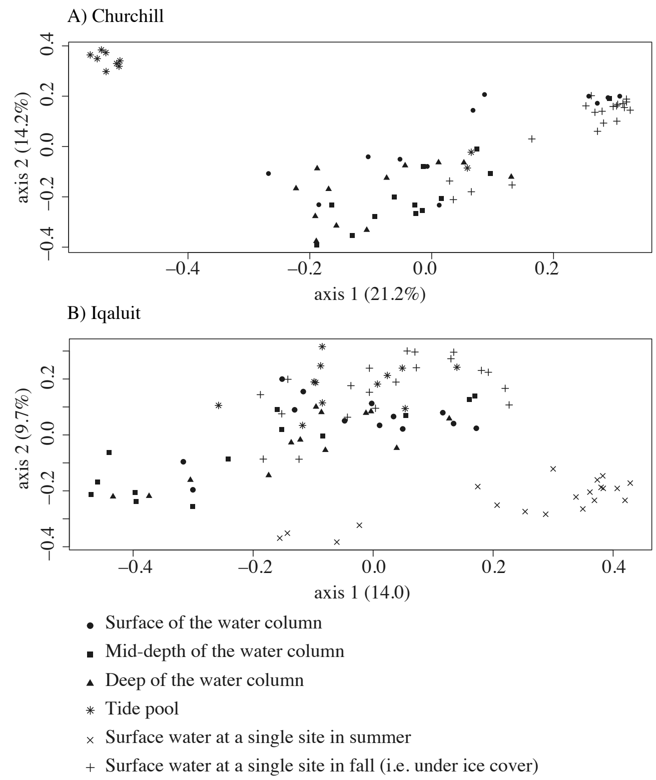


Figure 5. Principal component analysis depicting the community structure at the species level among sampling locations (water column (surface, mid-depth and deep water), tide pools (i.e. intertidal zone) and surface water collected in a single site in summer (i.e. S20) and in fall (F20) for both Arctic sampling ports at (a) Churchill and (b) Iqaluit.

Temporal and spatial eDNA distribution

Coastal biodiversity monitoring in the Arctic using traditional species diversity is generally limited to the summer season. In contrast to traditional surveys, eDNA surveys might be improved under the ice cover due to the limited UV exposition and cold water temperature promoting hence the eDNA preservation and detection[37]. On the other hand, the cold water temperature might reduce the metabolism of species

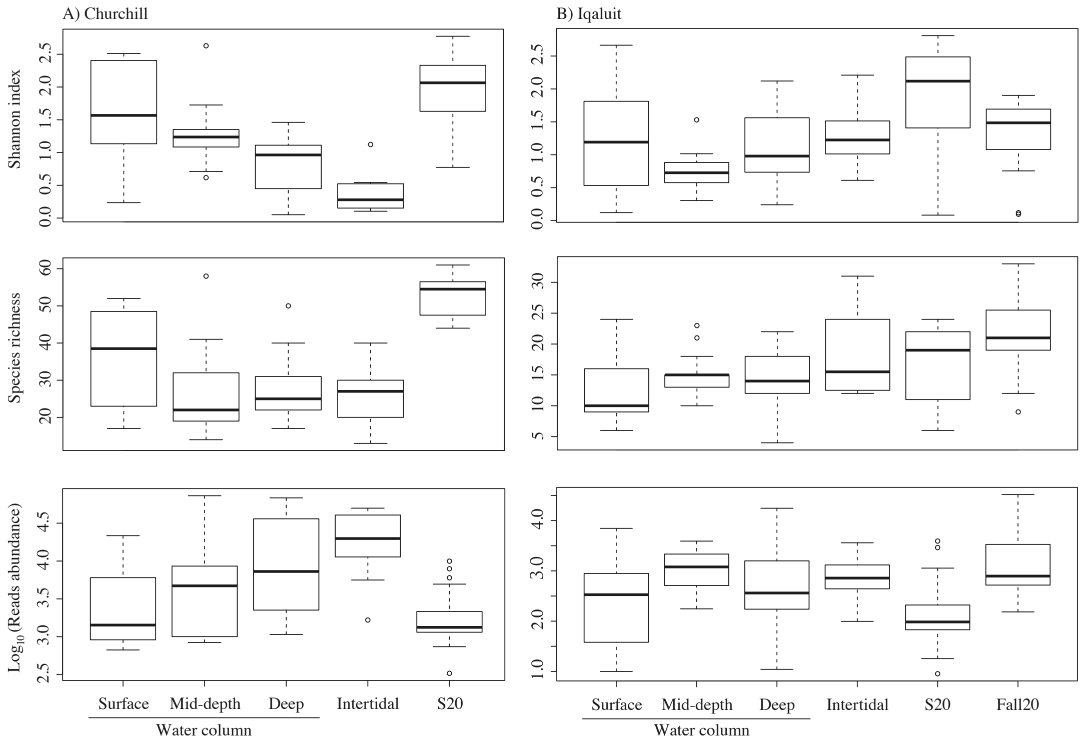


Figure 6. Boxplots comparing Shannon index, species richness and reads abundance detected using eDNA metabarcoding for each sampling location (i.e. water column (surface, mid-depth and deep), tide pools and S20 and Fall20) in (a) Churchill and (b) Iqaluit.

and therefore reducing the eDNA released/detection[38]. Here, water collected under ice cover showed high efficiency of eDNA metabarcoding and detected greater species richness than summer water collections. The latter is particularly relevant because the use of eDNA could expand the time window to survey coastal biodiversity in the Arctic, ease access to sites (i.e. no need of boat) and might provide information about the ecology of Arctic species under ice cover. Little is known regarding the life history of many coastal species under the ice cover. For example, Arctic species might be adapted to breed later in winter conditions. The recruitment of polychaetes may be later in summer in the Arctic compared to southern regions, which might explain their eDNA dominance during fall sampling. Further studies are therefore needed to evaluate the variability of eDNA through the year and how it may reflect Arctic species ecology (see Goal 2 spatial variation).

Little is known about how the eDNA distribution may depict the local spatial distribution of species, especially in marine ecosystems, a well-mixed ecosystem compared to freshwater. The eDNA species detection may vary as a function of the disproportionate amplification from unequal primers binding among species (as observed between both primer sets), the population density[15,39-43], local environmental conditions, life history traits and shedding rates among species groups[38,44]. Here, at the local scale, the eDNA distribution varied between habitats (i.e. water column and tide pools). In both ports, eDNA of Arthropoda and Annelida was more prevalent in the water column, whereas the eDNA of the Gastropod, *Littorina saxatilis*, a dominant species in tide pools (unpublished data), dominated in these areas. However, the large tidal area in Iqaluit increases the water mixture between tide pools and the open ocean, which may explain the lower

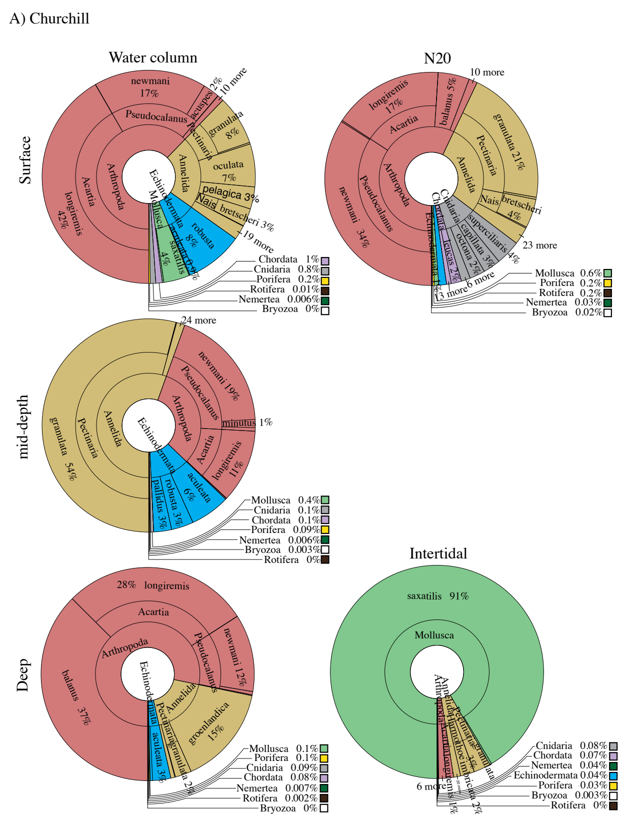


Figure 7a. eDNA community differences between sampling locations (i.e. water column (surface, mid-depth and deep), tide pools and S20 and Fall20) in Churchill. The different layers represent phyla (central), genius and species (peripheral).

community distinction between tide pools and the water column compared to Churchill. Moreover, the observed heterogeneity of eDNA within and between samples suggest that collecting at least 15 samples within a site across as many sites as possible in any given port is optimal to track the relative level of biological similarity, an important metric to detect effects of climate and shipping traffic change (see Goal 3). Hence, metazoan eDNA appears to be spatially heterogeneous within ports and is likely to provide a good representation of the local species distribution. The vertical eDNA distribution may vary as a function of the life cycles, transport and settling advection[45]. In rivers, the eDNA is expected to be transported over large distances[46,47]. Here our data support the idea that in estuarine conditions, such as Churchill, the freshwater flowing from the river increases the diversity in the surface water layer. Cross calibration between local taxonomic analyses and genetic characterization of biological communities will contribute to validating the eDNA efficiency for tracking the taxa dominance and informing the relative importance between the eDNA aggregation and the species distributions (see Goal 2 spatial variation, M.Sc. graduate student project). Comparing the eDNA distribution with the vertical distribution of the plankton may be used to evaluate the potential role of eDNA to reflect changes in the life stories due to global changes (see Goal 2 Bulk plankton metabarcoding).

Challenges and limitations

Beyond its many advantages and ease of use, the routine application of metabarcoding for Arctic monitoring requires overcoming some limitations. Here the eDNA metabarcoding identified *Acartia tonsa*, a potential invader that has been previously recorded in the ecoregions of connected Churchill ports[4]. However, a miss-identification of organisms in the sequence references might be possible. The accuracy of the eDNA method is directly dependent on the taxonomical effort within public sequence references. The eDNA method might eventually allow for less dependence on a large pool of expert taxonomists to conduct follow-up identification of organisms. For the time being however, taxonomist expertise is crucial for reducing biases of species distributions related to increasing use of large-scale eDNA metabarcoding. Furthermore, one of the main shortcomings of metabarcoding is the incomplete state of reference sequence databases. The better our knowledge of local species richness, potential invaders and genetic information, the better will be the accuracy of eDNA methods for detecting potential biodiversity shifts. Currently, a high proportion of the Arctic species have not even been sequenced yet; this is essential for refining identifications from DNA-based information. Despite considerable barcoding efforts, reference sequences are still very rare for

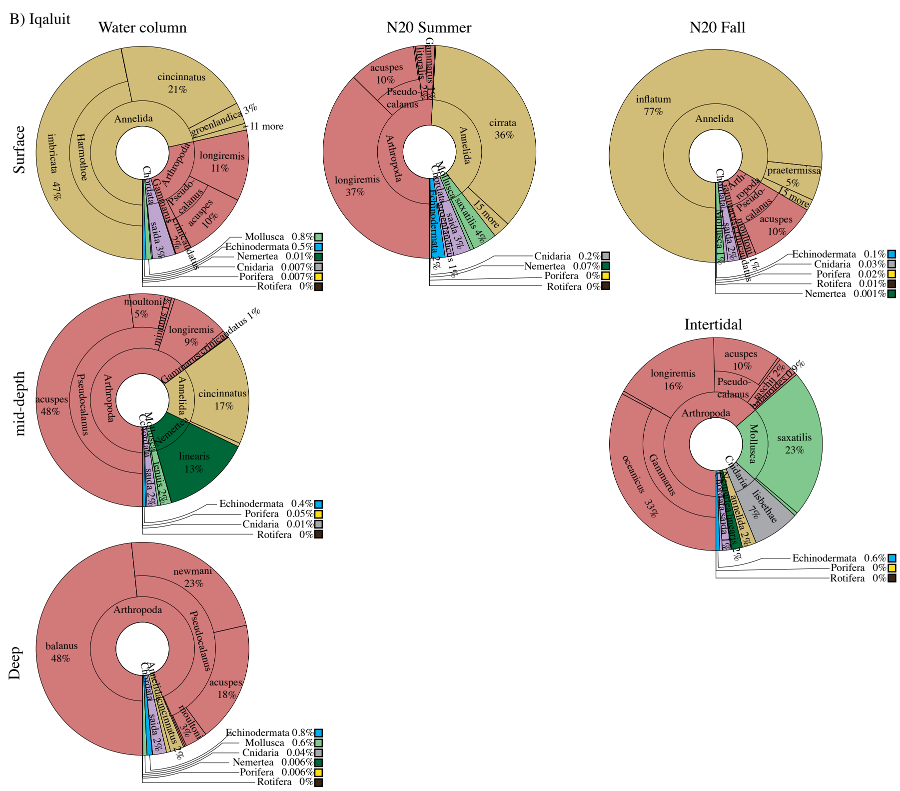


Figure 7b. eDNA community differences between sampling locations (i.e. water column (surface, mid-depth and deep), tide pools and S20 and Fall20) in Iqaluit. The different layers represent phyla (central), genius and species (peripheral).

coastal benthic species, especially for remote regions such as the Arctic. For this purpose, benthic specimens collected in ports are being preserved such that they could be used for future barcoding when funds will be available. The eDNA method is thus likely to improve through time.

Arctic conservation biology

We optimized water sampling strategies for remote regions by using a novel syringe method for filtering samples (this allows for sampling at multiple sites simultaneously, limits cross-contamination between samples and its simplicity allows inexperienced collaborators to collect additional eDNA samples relative to standard practices of using an electric pump), DNA preservation at room temperature (storing/shipping frozen samples in remote regions is

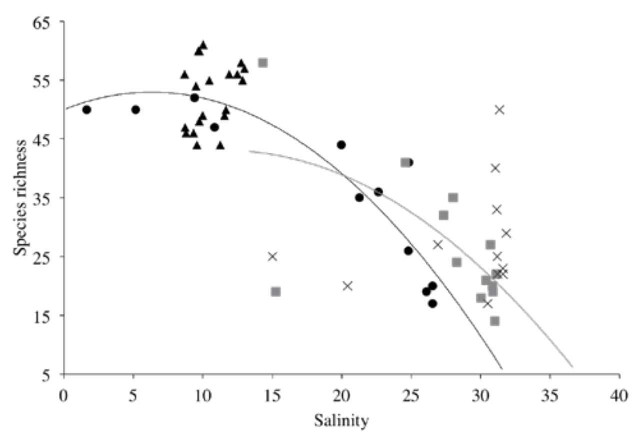


Figure 8. Relationship between the species richness detected using eDNA metabarcoding and the salinity of the water collected for the surface layer ($R^2 = 0.85$, black; circles: sampling water column and S20: triangles) and mid-depth samples ($R^2 = 0.44$, gray squares) and deep water (gray cross).

risky and often not possible), cost-effective extraction method (significantly increasing the ability to process large sample sizes) and by maximizing the level of genetic variability recorded at the species level (increasing the accuracy of biodiversity monitoring by targeting two COI mitochondrial genes[48]).

CONCLUSION

Our results to date are most promising as they clearly indicate that eDNA metabarcoding of water samples may be used to monitor coastal metazoan species in the Arctic. We show for the first time that eDNA is spatially and temporally heterogeneous within ports and that the efficiency of the eDNA monitoring surveillance is improved when sampling under-ice cover. By allowing rapid sample collection by experienced or novice individuals, reducing the cost associated with data collection/shipping and reducing manipulation of organisms, the analysis of eDNA from water samples will be a revolutionary tool to increase the power of detection, spatial coverage and frequency of sampling, thus improving detection of biodiversity shifts in large coastal Arctic ecosystems. We caution that metazoan eDNA appears to be spatially heterogeneous within ports, and that species assignments of molecular barcodes can be misleading at times due to errors in reference libraries. However, overall we conclude that, with proper replication and statistics, eDNA metabarcoding surveys can reveal global biodiversity patterns across a broad array of taxa. We provide recommendations for sampling and interpreting eDNA metabarcodes from commercial ports:

- Use similar eDNA collection, filtration, extraction, and sequencing methodologies when possible.
- We recommend collecting at least 15 samples within a site across as many sites as possible in any given port.
- When possible, sequence each sample at a depth of 75,000 reads for the COI primer set used here and a depth of 50,000 for the 18S primer set.

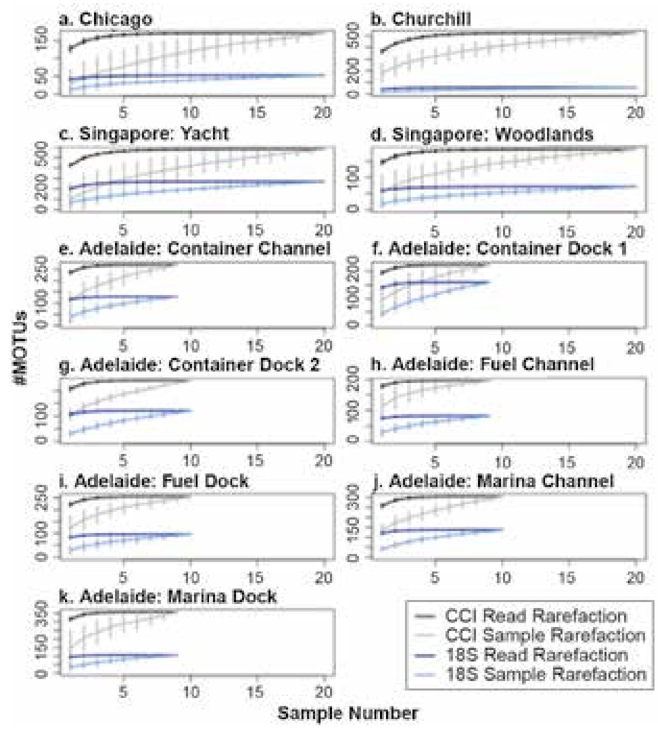


Figure 9. Rarified MOTU accumulation curves by read and sample numbers for each site. Solid black line denotes COI read rarefaction, grey line denotes COI sample rarefaction, dark blue line denotes 18S read rarefaction, and light blue line denotes 18S sample rarefaction. Errors bars represent 95% confidence intervals.

- When variation in sequencing and collection effort occur, rarefaction can be used to compare samples using classic diversity metrics, but several newer metrics (e.g. Chao Shared Species) can also allow similar inferences without loss of data.

ACKNOWLEDGEMENTS

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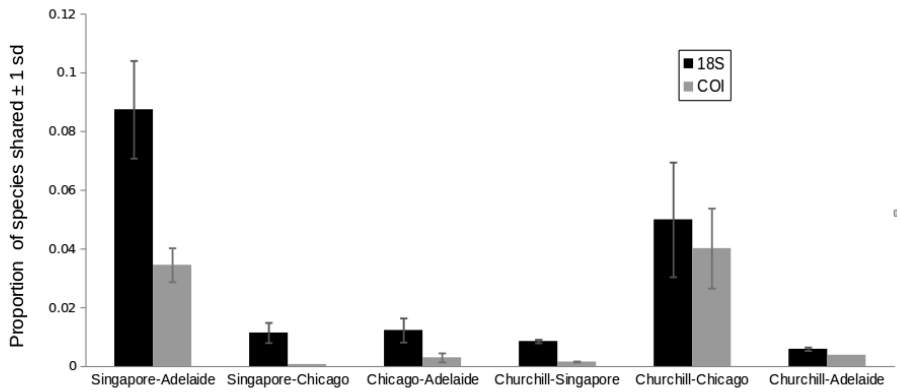

Figure 10. Estimated proportion of shared MOTUs among ports for the 18S dataset (black bar) and the COI dataset (grey bar). The estimation proportions were calculated by dividing the Chao Shared Species estimate by the sum of the Chao2 richness estimate for each site minus the Shared Species estimate. Error bars represent standard deviations.

the eDNA metabarcoding, to broaden the scope of that study to the international level and developing invasive predictive model integrating the Canadian Arctic coast. We thank Melania Cristescu and Guang Zhang for their help in chosing primers and Frederic Chain and Yiyuan Li for the pipeline development. Cathryn Abbott, He Xiaoping, Kara Aschenbrenner, Lowe Geoff and Scott Gilmore for sharing individuals to test in vitro primers and help improving our eDNA sediment extraction protocol. Rob Young for sharing sequences from Arctic species to test in silico primers and Éric Normandeau and Jérôme Laroche for the development of the bioinformatics pipelines. We are grateful to Noémie Leduc (Master student), Philippe Israël Morin, Charles Babin, Maëlle Sevellec, Brian Boyle, Cecilia Hernandez, Charles Babin, Eric Parent, Jésica Goldsmit, Rob Young, Valérie Cypihot, Farrah Chan, Guillaume Côté and Martin Laporte for their various supports. We also thank the following individuals for field assistance and participating in training: Frédéric Hartog, Christopher W Mckindsey, Nathalie Simard, Antoine Dispas, LeeAnn Fishback, Daniel Gibson, Dick Hunter, Austin MacLeod, Thomas Whittle, Rory McDonald, Frederic Lemire, Willie Keatainak, Adamie Keatainik, Marcusie and Willie (Jr) Keatainak. We thank Eric Solomon, Shelly Elverum, Alain Dupuis, Bronwyn Keatley for collaboration on the DFO OFSC project that allow us to extend the community based eDNA monitoring in Pond Inlet and Salluit. Many thanks to the Port of Chicago and the Singapore Yacht Club for our collaborators to sample on their property. This research is also funded by the Notre Dame Environmental Research Initiative and NSF Coastal SEES grant #1427157 awarded to David Lodge, as well as, POLAR knowledge, Nunavut Wildlife Management Board and the Fisheries and Oceans Canada Aquatic Invasive Species Monitoring Program.

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AUTOMATED ICE AND OIL SPILL MAPPING – PROTECTING ARCTIC COASTAL REGIONS AND COMMUNITIES

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ABSTRACT

Remote sensing, the science of aerial or satellite data capture of the earth, provides crucial information for such important endeavors as smart agricultural practices, shipping in northern waters, and monitoring of greenhouse gases. Vast amounts of data are generated, and computer-based algorithms to interpret the data are urgently needed. For example, using the Canadian RADARSAT-II satellite, Canadian Ice Service (CIS) personnel manually interpret 4000 scenes annually, providing ice type maps over huge (500 km by 500 km) regions. These maps can be used to infer ice thickness and ice strength to facilitate decision support systems for shipping and icebreaking. Also, CIS operates a manually operated system (ISTOP) designed to identify ocean-based oil slicks. To save time and money and to reduce human bias, there is a demand for machine algorithms that can analyze this imagery for ice type and oil spill detection. Our particular interest is the automated interpretation of radar-based imagery of ice-infested waters, a challenge due to the sensor characteristics and environment variability that confuse the ice types and confuses the appearance of oil slicks.

To effectively address this problem, multiple thrusts are required. Field work is required in the ice-infested regions to generate ground truth that validates the ice types and properties. Coincident satellite imagery is then used to correlate radar measurements with these ice types. Automated tools can then be developed and refined to identify ice, open water, and oil slicks. The new Canadian radar-based satellites, known as the RADARSAT Constellation Mission (RCM), are planned for launch in 2018 and algorithms dedicated to the new imaging modes on this series of satellites will be addressed as part of this project. The detailed maps we generate are important for ship navigation in hazardous waters (to reduce risk and save time and fuel) and to provide input into forecasting models. Oil spill detection is necessary as deterrence for intentional spills and as a means to support legal proceedings against such illegal activities. Other northern nations and oil companies would be interested in purchasing maps derived from the proposed algorithm.

KEY MESSAGES

- This project is developing next-generation satellite-based ice, ship, wind, and oil spill surveillance, detection, and identification system so that Canadians receive early warning of marine hazards with improved monitoring. Canadians will benefit since measures can then be taken to reduce the impact of these hazards on navigation and local communities. In addition, the same system supports the development of knowledge to assist understanding of climate change in ice-infested Arctic regions.
- Automated ice interpretation using synthetic aperture radar (SAR) imagery is important for rapid and accurate ice map generation to support navigation and environmental modelling.
- There is no known system that reliably detects oil spills in oceans. That the Arctic regions will have an increase in ship traffic over the coming decades is expected and this will increase risk of oil spills that can affect local communities and ecosystems.
- Remote sensing provides the only feasible means to identify oil spills over vast ocean regions but recognition is challenging due to winds and oil breakup. Our research is developing novel means to identify oil spill candidates in SAR imagery. Ground truth has been provided using the Canadian Ice Service (CIS) ISTOP (Integrated Satellite Tracking of Pollution) system.
- A protocol is being developed to evaluate the existing MAGIC (MAp-Guided Ice Classification software system) sea ice classification system across different seasons and locations, necessary for operational considerations.
- A new initiative with Dr. Derek Mueller (Carleton) to evaluate MAGIC algorithms to perform identification and tracking of ice islands is proceeding.
- An airborne ice thickness and roughness observation campaign has been performed in

April 2015 and acquired extensive data coincident with SAR imagery to facilitate algorithm development and validation.

- Relations between SAR backscatter and sea ice thickness depend on regional differences of multiyear ice backscatter, and multiyear fractions within pixels and regions of interest.
- Three new PhD students have been hired at the University of Waterloo to directly and jointly assist with the new research developments.
- Ship detection using SAR is a new initiative in this group. Using AIS data for validation, our preliminary results demonstrate a high accuracy rate with nearly 100% detection of known ships using synthetic aperture radar (SAR).
- We are actively communicating with third parties (PCI Geomatica, LookNorth, ASL Environmental, Canadian Ice Service) with regards to operational and commercial use of algorithms developed.

OBJECTIVES

Our project's objectives have grown since its inception. Our objectives now include:

1. Conduct research into algorithms to automatically create state-of-the-art simulated SAR images containing ice and oil slicks since natural such scenes are not known.
2. Investigate the potential to improve our existing binary ice and open water classification rate based on in-house existing algorithms for dual-pol SAR imagery by accounting for season and geographical region.
3. Create tools and apply these tools to dual-pol SAR imagery to generate our own in-house ground truth scenes that illustrate basic ice types (multi-year, first year, new) and open water.
4. Develop and evaluate automated algorithms to segment fine quad-pol and compact polarimetry (CP) SAR images and classify ice and water regions at available resolution.
5. Develop and evaluate automated algorithms to accurately identify basic categories of ice (multi-year, first year, new) and open water, using SAR dual-pol, fine quad-pol, and CP imagery without user intervention.
6. Develop automated oil spill detection algorithms using SAR dual pol, fine quad pol, CP imagery with true positive accuracy of 90+% and false negative accuracy 80+%.
7. Apply deep learning techniques to the automated interpretation of SAR sea ice imagery. More specifically, use convolutional neural networks to generate improved ice concentration maps, ice/water maps, ice typing maps, and oil slick detection.
8. Develop techniques to use SAR based ice concentration maps and ice/water information as inputs into data assimilation models to improve estimates of ice concentrations and thickness over large regions.
9. Assess the ability of MAGIC algorithms to demarcate, classify, and track ice islands in SAR imagery (in collaboration with Dr. Derek Mueller, Carleton University).
10. Develop methodologies to transfer algorithms to other scientists with a need to map ice and oil slicks and to CIS for consideration to be used operationally, and to transfer image output maps to the Inuit for evaluation on transportation in ice regimes.
11. Continue long-term observations of sea ice conditions and thickness of hazardous ice features in the Beaufort Sea, extending from the 2009 Beaufort Regional Environmental Assessment.
12. Obtain airborne validation data coincident with SAR image acquisitions. Retrieve quantitative information about ice morphology (roughness and ridging) and thickness

from those measurements to act as ground validation.

13. Create partnerships for end use of algorithms developed (PCI Geomatica, LookNorth, ASL Environmental Systems).
14. Develop and test numerical SAR models that are better able to identify ships and icebergs.
15. Develop and test numerical SAR models that improve ocean wave height estimation.
16. Partner with C. Duguay (Geography, University of Waterloo) to study the ability for the MAGIC system to segment SAR lake ice scenes.

KNOWLEDGE MOBILIZATION

From April 1 2016 to January 31 2017, the following mobilization activities took place.

- Eight journal publications submitted, accepted or published.
- Eight presentations at scientific conferences.
- Ongoing meetings with other researchers and companies; many of these are identified below, but it is difficult to track and include all of these.
- Multiple discussions with four companies and government agencies interested in partnering for enhanced algorithm development and usage.
- Regular research discussions with the Canadian Ice Service (CIS).
- March 2016: Face-to-face meeting with Leah Braithwaite (then Chief, Applied Science – Canadian Ice Service).
- April 2016: initial discussions with ASL Environmental with regards to automated ice mapping using MAGIC software applied to SAR imagery.
- June 2016: phone discussion with Trevor Bell with regards to SmartIce.
- Sept 2016: online demonstration of key research progress to the CIS Service; presented to Dean Flett and Tom Zagon.
- Sept 2016: follow-up phone discussion with Dean Flett and Tom Zagon to establish research priorities and a plan with CIS.
- August 2016 presentation to ECCC SAR data assimilation team on the retrieval of ice concentration from SAR using a CNN.
- Dec 2016 discussions with Derek Mueller (Carleton) with regards to defining ice island tracking algorithms.
- Dec 2016: meeting with Randy Scharien, Tom Zagon, Katherine Wilson at ArcticNet with regards to automated operational ice mapping for Pond Inlet in support of a northern community.
- Dec 2016: discussions with PCI Geomatica with regards to scene segmentation algorithm capability.
- Jan 2017: plan of action discussion with ASL Environmental with regards to joint grant proposal.
- Jan 2017: Skype with Derek Mueller (Carleton) to define specific objectives and to discuss data downloads to be used for algorithmic testing.
- Jan 2017: more focused discussion with PCI Geomatica with beta testing plans.
- Jan 2017: discussions with LookNorth to find receptor for ice concentration mapping algorithm.

INTRODUCTION

Satellite imagery is the only feasible means for monitoring the Arctic. Synthetic aperture radar (SAR) sensors flown on satellites provide a key data source for Arctic monitoring. The Canadian Ice Service (CIS) manually interprets 12000+ SAR images each year and this is expected to increase with increased Arctic shipping traffic and increased availability of SAR imagery due to the multi-satellite RADARSAT Constellation Mission (RCM) planned for 2018. RCM satellites carry a SAR called 'compact polarimetry' (CP) expected to improve ice and oil monitoring (Decker et al., 2014; Charbonneau et al., 2014) as well as wind speed predictions. Increasing ship activity in the Arctic demonstrates a critical reason to monitor ice conditions and oil spills to protect Arctic coastlines and to effectively serve remote communities.

Remote sensing of the Arctic is important to monitor sea ice, oil spills, and ocean winds. Sea ice, on a broad spatial scale, must be monitored in the Arctic since accurate estimates of ice thickness and type are critical for operational, scientific, and safety reasons. Information on ice extents and thicknesses serve as a basis for monitoring the progress of climate change. Ice thickness and drift, on a more localized scale, is important information when ice is used as a hunting and transportation platform (Laidler et al., 2011). Oil spills are seen relatively often on the sea surface (Brekke and Solbert, 2005). Deliberate oil spills occur with higher frequency than oil spills associated with ship accidents. The negative impact of oil spills on Arctic coastal regions may become significant with the expected increased ship traffic in these regions and a corresponding impact on seabirds, aquatic animals, and coastal ecology along shorelines including proximal to Arctic communities.

Ocean surface wind measurements are crucial to predicting ocean storms and to understand climate change. Momentum of the ocean surface is primarily caused by wind, impacting current systems as well as surface waves. Ocean surface wind speed and direction will assist weather forecasting accuracy when incorporated into associated models. Being able to estimate ocean wind speed has an impact on ship navigation, because strong winds lead to high waves that impact time at sea and fuel consumption.

SAR has always been used to monitor sea ice; however, developing computer algorithms that can correctly identify ice types, oil slicks, and wind speed in SAR imagery has been elusive. Incidence angle backscatter variations, high within-class class backscatter variability, masking effects of melting snow on ice, and wind variations are key challenges that thwart automated algorithms for such monitoring. Good success has been recently achieved by developing an algorithm within the MAGIC software system (Clausi et al., 2010) that uses an automated approach to identify ice versus open water (Leigh et al., 2013). SAR is well suited to scene capture of oil slicks but current technology suffers from automated identification of oil slicks due to false positives (many 'look-alikes') and false negatives (due to oil slicks, mimicking backscatter characteristics of the surrounding ocean). Building a better statistical understanding of the SAR backscatter would not only improve algorithmic identification of oil spills, but would improve our estimates of ocean wave height and ship detection.

MAGIC uses an advanced unsupervised classification algorithm demonstrated to reliably segment a SAR scene into visibly distinct segments (Yu and Clausi, 2007; Yu and Clausi, 2008). MAGIC uses this algorithm combined with a labelling model to provide an automated ice/water mapping system using CIS operational imagery (Leigh et al., 2013). The RCM will provide operational compact polarimetry (CP) scenes and this is expected to provide improved data for ice/water mapping, ice typing, oil spill identification, and wind speed estimation. Use of simulated CP data prior to RCM launch is a necessary research direction in support of future operational CP scenes. The use of deep learning approaches, namely, convolutional neural networks (CNNs) (Krizhevsky, 2012) is important to investigate improved scene segmentation performance.

ACTIVITIES

1. *Use of Deep Learning to Interpret SAR Sea Ice Scenes*

    - Convolutional neural networks (CNNs), a form of "deep learning", are being investigated to assess their capabilities for estimating ice concentration, binary ice/water classification, and ice typing in SAR imagery.
    - We have conducted preliminary research published at the ArcticNet 12th ASM whereby Sentinel-1 scenes were classified using CNNs into ice and water.
    - An accurate estimate of ice concentration at a high spatial resolution (on the order of 1km) is important for assessing the development of an oil spill and its impact on the marine environment.
    - We have designed a deep learning based convolutional neural network (CNN) that is able to refine ice concentration estimates provided by operational ice charts into detailed pixel-by-pixel ice concentration estimates.
    - L. Wang (PhD completed) implemented the CNNs for ice concentration and this research has been published in two journal papers and two conference papers.
    - L. Xu (PDF) has implemented prototype CNNs for ice/water classification using SENTINEL-1 data.

2. *Ice Island Automated Identification and Tracking in SAR Imagery*

    - SAR data of ice islands has been provided by Dr. Derek Mueller (Carleton) .
    - Currently, ice islands are manually identified and tracked in the SAR imagery which is highly time consuming.
    - Goal is to develop algorithmic methods to automatically identify and track through time ice islands.
    - M. Ghanbari (PhD candidate) has started research on this problem.

3. *Improving MAGIC Software for Operational Use*

    - Completed software requirements as per CIS needs to allow MAGIC to input and output standard georeferenced data for use at CIS.
    - Implemented method in MAGIC to adjust output colours on classification results.
    - M. Stone, a co-op student hired during the Spring 2016 term, completed this work.

4. *Compare Simulated CP data for Scene Segmentation*

    - Convert quad-pol to simulated compact polarimetry (CP) imagery.
    - A method to utilize full complex quad-pol data for SAR scene segmentation has already been developed (polarIRGS).
    - We are developing a SAR scene segmentation approach using complex CP data, similar to polarIRGS.
    - Eventually, compare dual-pol, complex quad-pol, complex CP, and features derived from simulated CP for SAR scene segmentation.
    - Initially using quad pol data used by Dabboor and Geldsetzer (2014) to evaluate these algorithms.
    - M. Ghanbari (PhD candidate) has initiated research on this topic.

5. *SAR Sea Ice Imagery Acquisition and Training/Test Data*

    - Previously, we have produced pixel-level ice/water training/test data of 63 full SAR scenes (10k x 10k) in the Beaufort Sea validated by an ice analyst.
    - We have created training/test data using of this data by breaking up ice into constitutive categories, namely, multi-year, first year, and new ice.

- Field studies, from other time periods, have provided field captured ground truth coincident with RADARSAT-2 scenes.
- For this data, we have also created a method to quickly generate pixel-based training/test data to train a classifier and to test the ability of that classifier.
- M. Stone (undergraduate co-op student) has completed this implementation.

6. *Multi-Class Ice Classification*

- We are able to perform binary (ice/water) ice classification using dual-pol RADARSAT-2 imagery.
- We are in the process of extending this to multi-class (water, multi-year ice, first year ice, new ice) classification.
- The SVM we used for binary segmentation may not be effective for the multi-class case so we are planning to utilize a random forest classifier (Breiman, 2001) or rotation forest (Rodriguez, 2006) in its place.
- M. Zhang (PhD candidate) has started research on this work.

7. *SAR Oil Spill Identification in SAR Imagery*

- From CIS, we previously acquired 180 oil spill SAR scenes from the ISTOP program, based on nine years of observations during 2004-2012. These scenes are dominated by RADARSAT-1 ScanSAR-wide HH observations. There are only several dual- and quad-pol RADARSAT-2 images and they are all from 2012.
- All images contain at least one oil spill candidate that was identified by a CIS expert. The boundaries of the identified dark-spots are provided in shapefile format.
- Identified dark-spots have been categorized into three categories based on their proximity to the nearest ships. Oil spill candidates associated with ships are classified into Category 1A, which means they have the highest possibility to be true oil spills, and consequently the highest priority to be verified by aircraft. Candidates that have ships within 50 km of distance are classified into Category 1B, while those that have no ships within 50 km are classified into Category 2. Potential oil spills with relatively low confidence are Category 3.
- Two journal publications have been created during this reporting year: one that is used for identifying the necessary dark spots in SAR imagery (published) and the other a description of a novel active learning approach for classifying dark spots as oil spills (submitted).
- Research lead by Y. Cao (visiting scholar) and L. Xu (PDF).

8. *Evaluation of MAGIC Algorithms Across Seasons and Location*

- Graduate student (M. Ghanbari) has started to work on using MAGIC algorithms across different time periods for the same geographic regions.
- Started developing a test protocol to evaluate MAGIC algorithms across different geographical regions using the same time period.
- Software that can be used to simulate compact polarimetry from quad-pol SAR data (Charbonneau et al., 2010) has been provided by Environment Canada via CIS. This will allow us to convert oil spill and sea ice quad-pol scenes to CP format and features for evaluation. CP format is critical since the future RCM (RADARSAT Constellation Mission) will utilize this mode.

9. *Application of MAGIC Algorithms to the Classification of Lake Ice*

- Graduate students M. Hoekstra and J. Wang applied the MAGIC algorithms to the segmentation of SAR lake ice imagery.
- We are planning to implement a labelling algorithm to the classification of this data using texture features.

- Currently, planning to apply to extend to larger set of data.

10. Numerical Modelling of SAR Backscatter Using GRECOSAR

- A significant amount of time (18 months) was spent learning and applying the commercial GRECOSAR (licensed by GMV) software which was claimed to be able to model the SAR backscatter of a moving ship on the sea surface.
- This software was not trivial to use and, over time, it became apparent it was not able to properly model the ocean surface backscatter, as claimed.
- This was finally confirmed when the backscatter from GRECOSAR was compared to the known backscatter from a calibration corner reflector yielding different results. After 18 months of trials, GRECOSAR was abandoned.

11. Ship/Iceberg Detection Using SAR

- A three stage ship detection algorithm was developed and tested on simulated CP data using RADARSAT-2 scenes. A constant beta LUT was required to obtain the proper dynamic range and scenes were ordered via the SOAR program.
- The ship detection algorithm was applied to the SAR scenes and ground truth obtained using AIS data. High accuracy was obtained using the new modelling approach.

12. Wave Height Estimation Using SAR

- We have started developing a new wave height SAR model. CWAVE, developed at DLR, is based on ERS-2 wave mode data and has also been adapted to ENVISAT wave mode data.
- Our new model is based on using simulated CP data using RADARSAT-2 FQ data, in anticipation of the RCM 2018 launch.

13. Field Work Activities

- An airborne ice thickness and roughness observation campaign has been performed in April 2015 and April 2016 over the Northwest Passage and Beaufort Sea and acquired extensive data coincident with SAR imagery to facilitate algorithm development and validation.
- MEOPAR funds this research.
- Drifting buoys were air-deployed to facilitate tracking of ice features in SAR images. These buoys also served to follow the ice's fate into the summer melt season.
- Both a laser scanner and camera system was installed on the aircraft and operated coincidentally with the ice thickness sensor, thus providing swath data of surface roughness and pressure ridges.

RESULTS

1. Convolutional Neural Networks for SAR Sea Ice Concentration

A new approach for estimating ice concentration from dual-pol RADARSAT-2 imagery during the melt season has been created and tested using CNNs (Figure 1). The ice concentration maps that are generated have far more detail than the operational maps currently used which are typically derived from passive microwave scenes (Figure 2). The CNN algorithm has been successfully applied to the estimation of ice concentration (Wang et al., 2016a; Wang et al., 2016b).

2. Convolutional Neural Networks (CNNs) for SAR Ice/Water Classification

Our preliminary study for automatically identifying ice and water in SAR dual-pol scenes proved highly successful (Xu and Clausi, 2016b). The cross-pol scene of Envisat is known to be very noisy as noticed by

Figure 3. Even with this tremendous noise source, the CNN is able to segment ice and water successfully. Here we trained a CNN on five scenes and tested successfully on 15 scenes. This preliminary study encourages us to put more resources into CNN evaluation for SAR scene analysis.

3. Oil Spills – Dark Spot Detection and Classification

We have made strong progress developing a technique to detect dark spots in SAR ocean imagery with the intent to identify all the potential oil spill candidates (Xu, et al., 2016a) (Figure 4). The conditional random field approach is novel compared to the basic thresholding approaches currently found in the research literature. Further, we have performed active learning in order to improve the classification rate of suspect dark spots as oil spills (Cao, et al., 2016a; Cao et al., 2016b). We plan to extend our testing to data recently received from CIS from the Coal Oil Spill (Hornafius, 1999).

4. Create Method to Simulate SAR Imagery Containing Sea-Ice and Oil Spills

Although the synthesis of the synthetic aperture radar (SAR) imagery with both sea ice and oil spill can significant benefit in improving the consistency and comprehensiveness of testing and evaluating algorithms that are designed for mapping cold ocean

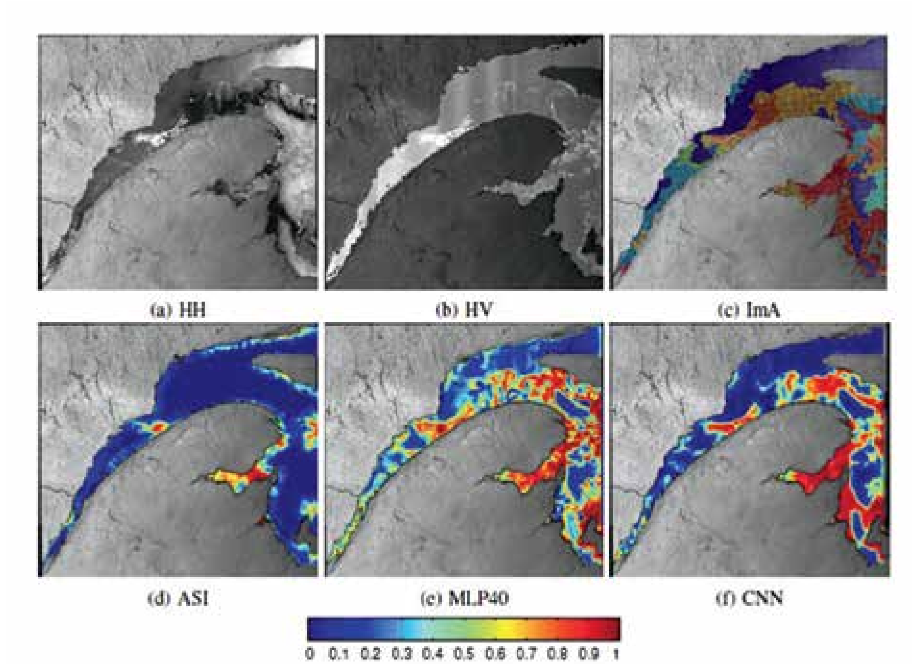


Figure 1. The ice concentration estimation result by CNN compared to ASI and MLP40 ice concentration for SAR scene. (a) and (b) represent the HH and HV pols, (c) is the corresponding image analysis chart, (d) represents the results using the known ASI algorithm, (e) represents results using a neural network MLP40, and (f) is the result using our designed CNN. Our CNN method provides a more realistic and accurate interpretation of the ice concentration.

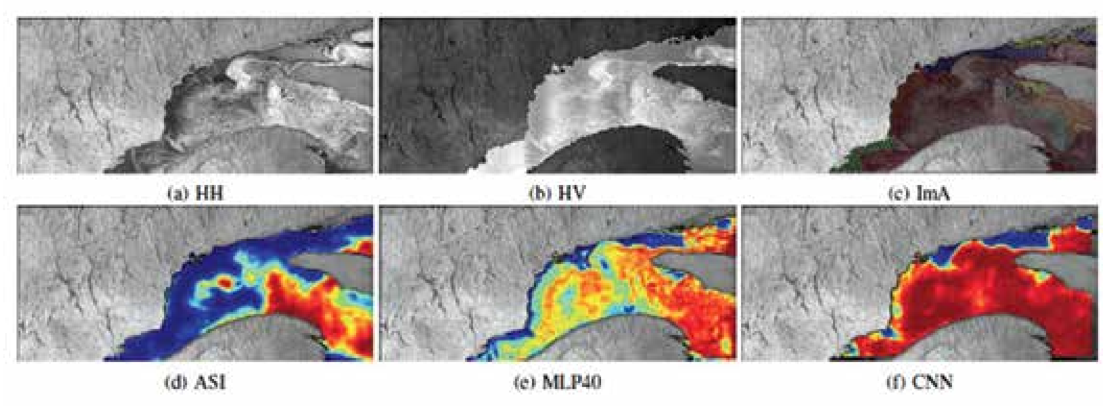


Figure 2. Similar to Figure 1, but showing a different SAR scene. The results again demonstrate the superiority of the CNN method to produce more detailed ice concentration maps.

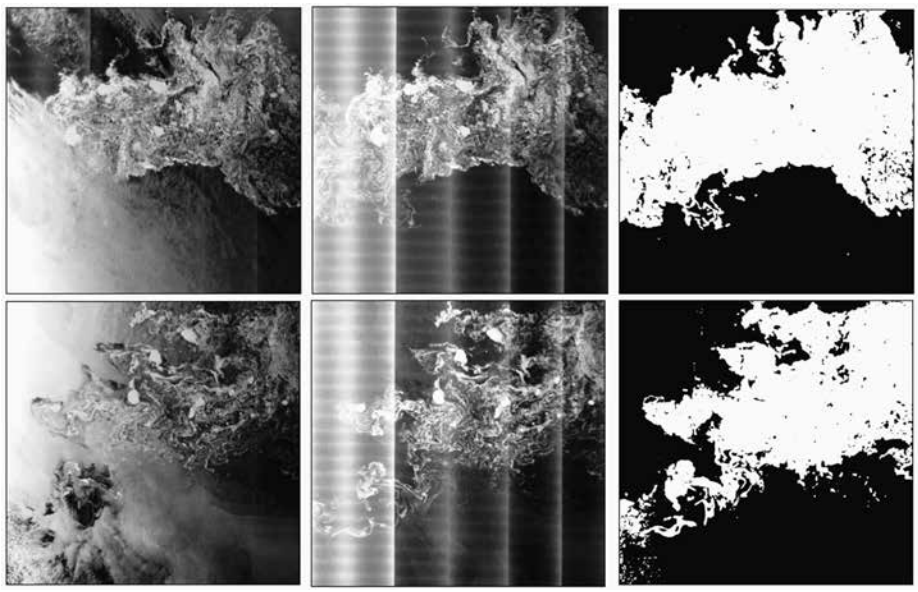


Figure 3. Two examples of successful application of trained CNN applied to two Envisat SAR scenes. First column is the HH-pol, second column is the HV-pol, and the third column is the output of the CNN successfully identifying ice and water regardless of the high noise content of the HV-pol.

regions, creating such an imagery is difficult due to the heterogeneity and complexity of the source images. We developed an enhanced region-based probabilistic posterior sampling approach to effectively synthesize SAR imagery with different ocean features (Xu et al., 2016c). The experiments demonstrate that the proposed approach can better address the difficulties caused by the heterogeneity in the source images compare with existing state-of-the-art ice synthesis method (Figure 5).

5. *Lake Ice Classification Using MAGIC*

We were successful in applying domain MAGIC segmentation algorithms to the classification of lake ice (Figure 6). The software was used by a pair of Geography graduate students who were also able to evaluate the user interface and provide feedback on the usability. This work was presented at the American Geophysical Meeting in two separate presentations as well as at the recent ArcticNet Science Meeting (Hoekstra et al., Wang J et al.).

6. *Weakly-Supervised Classification of SAR Imagery*

Weakly-supervised methods involve utilizing only a very limited number of training samples to guide the segmentation and labelling process. We have developed an accurate method for performing a weakly-supervised classification and demonstrate this method on SAR sea ice imagery (Xu et al., 2016d).

7. *Ship/Iceberg Detection Using SAR*

The ship detection algorithm produced results that were impressive with nearly 100% detection of AIS ships. Other targets could not be confirmed because these targets did not have any corresponding AIS data, which means the false alarm rate could not be calculated.

8. *Post-Field Work Data Processing*

Based on data captured during the airborne field campaign performed in April 2015 it was found that the larger-than-average multiyear ice thickness in April

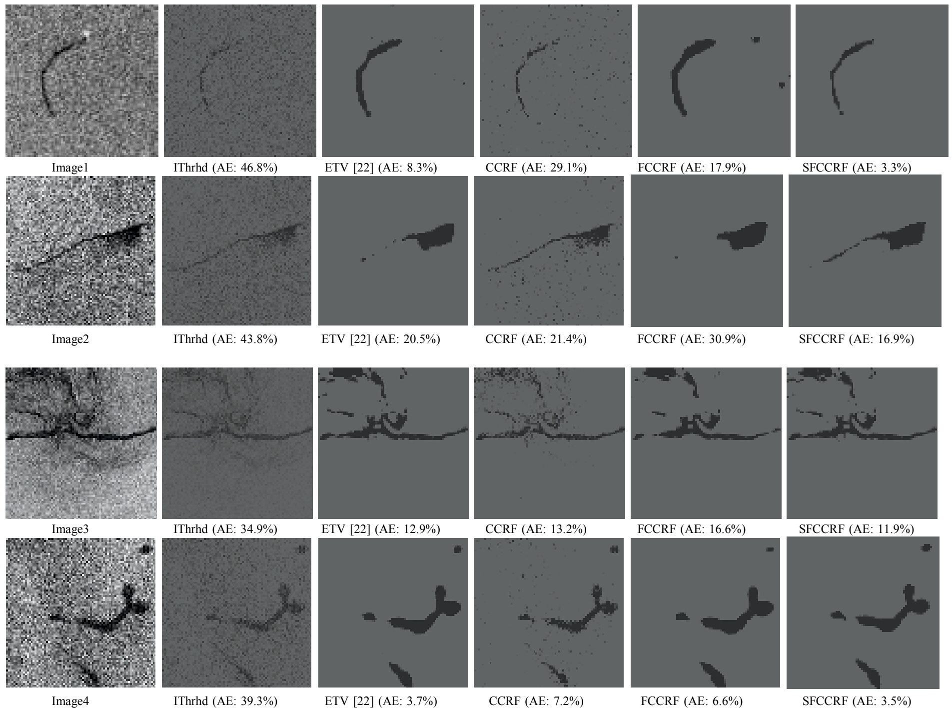


Figure 4. Detection of oil spill candidates by five different methods on four images. Comparing with the other methods, the proposed SFCCRF method is less affected by the background and target heterogeneities, and in the meantime can more accurately identify the boundaries and the linear targets.

2015 led to the survival of a unique ice band in the Beaufort Sea well into August, showing the importance of initial ice conditions for seasonal predictions of summer sea ice. A similar situation was found in 2016 with regards to multiyear ice. However, the thickness of first-year ice was up to 50% less than previously, leading to some of the observed, unusual early summer (May, June) ice retreat.

DISCUSSION

SmartICE (Sea-Ice Monitoring and Real-Time Information for Coastal Environments, http://smartice.org/) "seeks to address information needs using networks of in situ sensors that generate daily observations of changing sea ice conditions at hazardous travel locations, particularly during freeze-up and break-up, combined with user-based satellite image classifications of sea ice state." Discussions with Dr. Trevor Bell have indicated that an automated approach to satellite image classifications would useful to SmartICE and a relationship between SmartICE and the research team will be pursued. This will open opportunities to interact with Inuit communities to learn more about how remote sensing technologies and automated ice mapping can help with their daily lives in ice regimes. We wish to incorporate Traditional Knowledge into the development of the automated ice classification system so that output ice types are meaningful to Northerners. The Inuit use the coastal and MIZ ice differently than commercial shipping and so we wish to 'classify' it differently as per Inuit terminology.

The Canadian Ice Service (CIS) has an active interest in being able to automatically identify sea ice in SAR imagery. Ice maps produced by the CIS can be used to infer ice thickness and ice strength to facilitate decision support systems for shipping and icebreaking. The

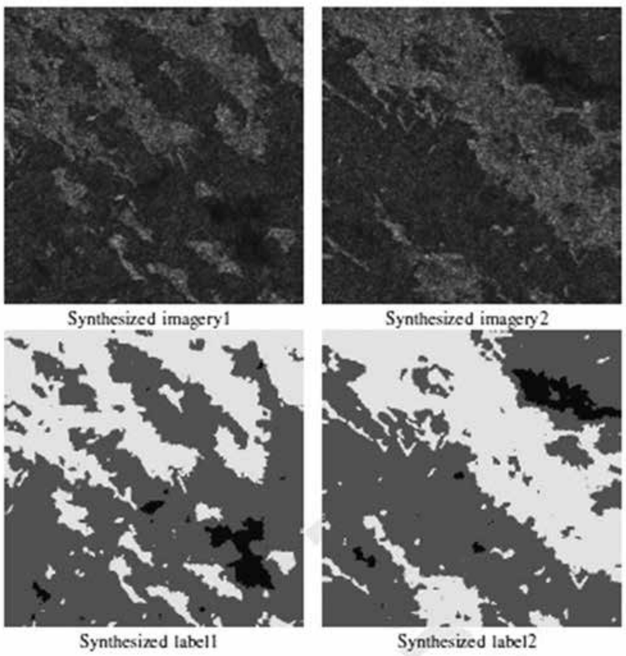
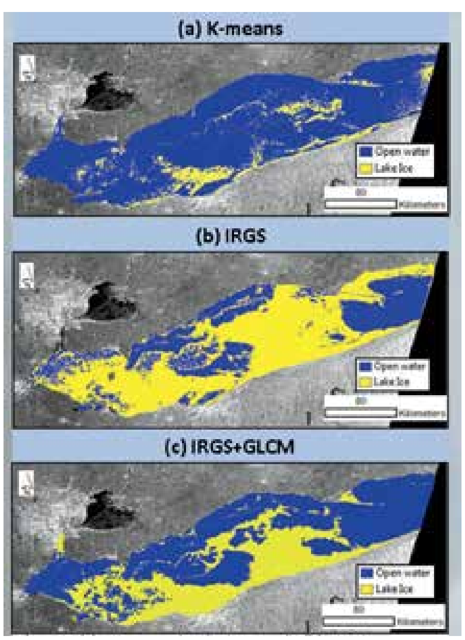


Figure 5. Two examples of synthesized SAR scenes with ice, water, and oil and accompanying scene with labels.

existing approach within the MAGIC system (Leigh et al., 2014) is used for binary pixel-level classification of ice and open water. In support of CIS operations and an interest in being able to provide ice maps more readily to Arctic peoples, we are assessing the capabilities of this algorithm across different ice types (multiyear, first year, and new ice), across different regions (Beaufort Sea and Hudson Strait, for now), across different time periods (to evaluate performance in the complicated freeze-up and melt periods), and using simulated CP in anticipation of the RCM launch. We are also assessing the capabilities of deep learning algorithms (in the form of convolutional neural networks) to improve the robustness of automated interpretation of SAR imagery.

CIS operates a manual system (ISTOP) designed to identify ocean-based oil slicks. Similar to sea ice, we are investigating the performance of segmentation algorithms to identify and classify oil spills. Even the ability to flag all dark spot candidates with potential to be oil spills is important given the vastness of the oceans, the high volume of data expected with the



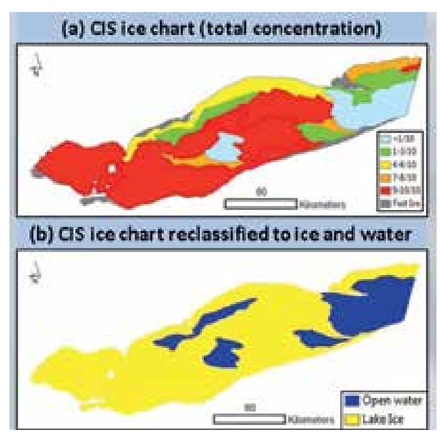


Table 5: Accuracy assessment of the three methods

Segmentation methods	Overall accuracy	Open water error	Ice error
K-means	34.69%	1.72%	63.57%
IRGS	74.39%	5.70%	19.91%
IRGS + GLCM	59.37%	1.14%	39.48%

Figure 6. A comparison of classification tests for lake ice SAR scene. K-means, IRGS, and IRGS + texture features are compared with the later showing the best performance.

RCM, and the impossible task of manually searching all such data. We are expecting that CP data will enhance the detection of oil spills (Li et al., 2014; Yin et al., 2015).

The enhanced ability to derive ice, oil, and ocean wave information from SAR imagery is important for ship navigation in hazardous waters (to reduce risk and save time and fuel) and to provide input into forecasting models. Oil spill detection is necessary as deterrence for intentional spills and as a means to support legal proceedings against such illegal activities. Other northern nations and oil companies would be interested in purchasing maps derived from the proposed algorithm.

ACKNOWLEDGEMENTS

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ARCTICNET LONG-TERM OCEANIC OBSERVATORIES: CONTINUATION AND SYNTHESIS OF THE EXISTING DECADAL RECORDS OF PHYSICAL AND BIOGEOCHEMICAL SIGNALS

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ABSTRACT

Since 2002, ArcticNet and its partners have deployed Long-Term Oceanic Observatories (LTOO) in the Beaufort Sea and elsewhere in the Canadian Arctic. These LTOO consist in lines of recording instruments anchored on the seafloor and maintained at different depths in the water above by floats. The instruments record the speed and direction of currents, the salinity, temperature, and nutrient content of the water, the abundance of chlorophyll (a pigment proportional to microalgal abundance), and ambient noise including the vocalizations of marine mammals. In addition, some moorings carry sediment traps, which are large automated funnels that intercept and bottle at regular intervals the plankton particles raining from the surface layer of the ocean. Such particles include ice algae, phytoplankton (vegetal cells), zooplankton (planktonic animals), zooplankton fecal pellets and all sorts of detritus, which are all excellent indicators of the intensity of different ecosystem processes taking place in the surface ocean. The LTOO are deployed at a given time and recovered and redeployed again after one year. As years accumulate, the time-series of particle rain recorded by the sediment traps will detect any long-term change in the ecosystem linked to climate change and associated shifts in the temperature, salinity or sea ice regime in a given region. By 2018, the ArcticNet LTOO will have accumulated 16 years of plankton rain in the Beaufort Sea. The objective of the ArcticNet-LTOO project is to recapitulate variations in this 16-year record to detect any response of the ecosystem to recent changes in the Beaufort Sea environment. If such a response was detected, it likely would represent the very first symptom of a shift of the Arctic pelagic food web towards a more boreal food web, with all the expected modifications in the services (e.g. food, health, revenues, skins, cultural bonding, etc.) provided to local communities by the present ecosystem. An additional objective of the project is to reconsolidate the former LTOO in Baffin Bay to help understand ocean circulation and biogeochemical fluxes in this region.

KEY MESSAGES

- Warmer conditions resulted in a fall bloom in 2012 that led to the early upward migration of herbivorous copepods the following spring in the Beaufort Sea, creating a mismatch between phytoplankton and zooplankton.
- The late snow and sea ice retreat in the Beaufort Sea in 2013 also contributed to the mismatch between phytoplankton and zooplankton as the ice algae release and the pelagic bloom occurred at the same time, impeding food availability later in the season for nauplii hatched at the time of ice algae release.
- Fall blooms contributed significantly to the annual export of phytoplankton in the Chukchi Sea, with export fluxes in October and November 2015 as high as during June and July 2016.
- LTOO data highlighted a slight overestimation of temperatures and surface salinity modeled with the CREG12 model (CMC-Environment Canada), but the model reproduced with satisfying accuracy and reliability major surface patterns observed in the Beaufort Sea.
- The first seasonal dataset of dinoflagellate cysts from a sea-ice-covered region reflected regional variations in fluxes between the eastern and western Hudson Bay and indicated that species-specific timing of cyst production is linked to the sea-ice cycle.
- Recurrent erosion of upper slope sediments due to current surges are driven by both wind and ice motion stress during storm events at the shelf break in the Canadian Beaufort Sea. Downwelling events facilitate the transport of shelf break sediments to the slope.

OBJECTIVES

Our objectives for the ArcticNet Phase IV project are:

1. to continue and expand the deployment of long-term oceanic observatories in Canadian and international waters;

2. to synthesize the year-round monitoring of pelagic ecosystem function from 2002 to 2018 in the Beaufort Sea; and

3. to investigate the formation of the North Water and the ice edge in Baffin Bay.

Objective 1 - Continuation/expansion of LTOO in Canadian and international waters

Long-term time series of arctic observations are extremely rare and the LTOO series have become invaluable. As instrument complexity and logistic costs explode, maintaining the LTOO increasingly requires external expertise and means. In close partnership with two major initiatives under the ArcticNet umbrella, objective 1 is to maintain existing LTOOs in the Beaufort Sea and develop new ones in Baffin Bay. Funded for four years by the Environmental Studies Research Funds (ESRF) and led by ArcticNet and IMG-Golder, the integrated Beaufort Observatory (iBO) is an ocean-sea ice-atmosphere observing system that was established in 2015 in the Beaufort Sea through the deployment of moorings. The primary goals of iBO are 1) to enhance the viability and safety of Beaufort oil and gas development through systematic observation of the marine environment and consequent advances in our understanding of Beaufort oceanography; 2) to enhance the numerical models required for planning and review of offshore activities throughout the region, and 3) to inform the permitting/approvals process by collecting and analyzing data on ice and ocean conditions, and make this data available to northern residents, industry, regulators, and other stakeholders. The project's central element in achieving these goals is the deployment, enhancement and maintenance of a series of integrated state-of-the-art environmental in situ and remote technologies deployed on ocean moorings, fixed or drifting with ice, from vessels, and from satellite-based systems in the Beaufort.

Green Edge is an international project on the dynamics of the phytoplankton spring bloom at the ice edge in Baffin Bay with sampling conducted in 2015 and 2016. The central objective of Green Edge is to predict the fate of microalgal production and the related carbon transfer through the food web and toward the sediments over past centuries and into the next decades. A key piece of information for Green Edge is the formation of the ice bridge in Nares Strait that dictates the dynamics of the North Water and the timing of the ice edge in Baffin Bay.

In addition to monitor changes in the Beaufort Sea and Baffin Bay, recent collaborations with the Alfred-Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) in Germany have extended the LTOO program to the HAUSGARTEN observatory in Fram Strait. The joint deployment of sediment traps and moored profilers recording temperature, salinity, and chlorophyll a in the East Greenland Current and the West Spitsbergen Current will allow further investigation of the variability in the magnitude and composition of export fluxes in relation to the temperature-salinity signature of water masses and sea ice concentration in the Arctic Ocean. Also, starting in 2015 in the Western Arctic Ocean, the addition of sediment traps on an existing oceanographic mooring (Chukchi Ecosystem Mooring) managed by the Alaska Ocean Observing System (AOOS) on the northern Chukchi continental shelf will enable LTOO to assess the biological response to changes in physical properties in the Pacific Arctic region, adding to our investigation of the variability in export fluxes in different water masses. Finally, an oceanographic mooring carrying a sediment trap was also deployed in the Queen Maud Gulf in the Canadian Archipelago as part of a pilot study regrouping partners from the W. Garfield Weston Foundation, Parks Canada, Québec-Océan and ArcticNet. The Queen Maud Gulf mooring will provide new and unique information on the circulation patterns and annual cycle of biological production in the Kitikmeot region.

Objective 2 - Year-round monitoring of pelagic ecosystem function from 2002 to 2018 in the Beaufort Sea: a synthesis

Sediment trap records have been maintained since 2002 on the shelf break and in Amundsen Gulf in the Beaufort Sea. Objective 2 is to recapitulate and synthesize variations in the magnitude and nature of export fluxes (an index of pelagic ecosystem function) in relation to the temperature-salinity signature of water masses and sea ice concentration on and off the Beaufort Sea Shelf over the full record duration and until 2018.

Indices of the magnitude of the fluxes such as total particulate matter (TPM), particulate organic carbon (POC), and particulate nitrogen (PN) are already available for all deployments before 2014-2015. Additional microscopic analyses will be conducted for the investigation of decadal variations in the nature of the exported material as a proxy for change in ecosystem function. Variables will include the timing, amount, and composition of sinking ice algae and phytoplankton; the abundance and developmental stages of key zooplankton swimmers; the size of lipid sacs in herbivorous copepods; and the size frequency of fecal pellets. Mooring deployments during the last phase of ArcticNet will maximize this time series.

Objective 3 - Formation of the North Water and the ice edge in Baffin Bay

The LTOO oceanographic datasets obtained in 2005-2006 in northern Baffin Bay remains underexploited. We proposed to valorize existing physical data and redeploy the LTOO in the North Water in support of the development of a state-of-the-art high-resolution (eddy resolving) coupled ice-ocean numerical model covering the entire Baffin Bay, from Davis Strait to the Lincoln Sea, including the seasonal ice-edge targeted by Green Edge. For the first time the LTOO deployment plan will be designed to support model development and to address the following specific questions: 1) what drives of the variability of the Atlantic waters entering with the West Greenland Current, 2) what are the potential sources of Baffin Bay deep and bottom waters, and 3) how are deep, intermediate and upper ocean layers connected in the Smith Sound frontal region. The circulation model will provide crucial background information for Green Edge, and will eventually inform plans for oil exploration in the region.

KNOWLEDGE MOBILIZATION

- Eight presentations at scientific conferences
- Several manuscripts in preparation
- One M.Sc. completed
- Participation to an internship at the Alfred-Wegener Institute for Polar and Marine Research, Germany
- Participation to a graduate course in Arctic marine zooplankton at UNIS, Svalbard

INTRODUCTION

A substantial reduction in Arctic sea ice extent, thickness, and volume has occurred in the last decade (Laxon et al., 2003). Concurrently, warming of the Pacific Water (Woodgate et al., 2006) and Atlantic Water (Walczowski and Piechura, 2006) flowing into the Arctic Ocean through Bering Strait and eastern Fram Strait respectively have been reported, with pulses of warmer Atlantic Water recorded as far as the Canada Basin (Polyakov et al., 2005). Such changes have had profound impacts on the ecosystems and ecosystem services of the Bering Sea (Grebmeier et al., 2006). How will they affect the circulation and ecosystems of the Canadian Arctic Ocean? During this short period of rapid physical changes in the Arctic Ocean, ArcticNet's long-term oceanic observatories (LTOO) obtained year-round physical and biogeochemical measurements in the Canadian Beaufort Sea since 2002. Except for two overwintering expeditions of the *Amundsen* in 2003-2004 and 2007-2008, ship-borne observations of the ecosystem are limited to the season of minimum ice extent from August to October of each year. Although less comprehensive, the set of variables recorded by the ArcticNet-LTOO are particularly precious because they provide a view of the complete annual cycle of some key aspects of the marine environment and its pelagic ecosystem over several years.

In their 1989 paper, Robert H. Bourke, Victor Addison and Robert Paquette, all from the Naval Postgraduate School, reported results obtained from the second scientific expedition that monitored Nares Strait in its entirety in order to characterize pathways of Arctic intermediate waters and determine whether they can constitute a possible origin for deep and bottom waters of Baffin Bay (Bourke et al., 1989). This expedition was conducted aboard the CCGS *Sir John Franklin*, today's CCGS *Amundsen*. Their study concluded that Arctic Waters couldn't form Baffin Bay deep waters due to significant mixing occurring in Smith Sound. This conclusion led the authors to suggest that the most probable source of dense waters would be those formed in winter during polynya events on the shallow Greenland shelves. Despite the extensive oceanographic sampling that occurred in northern Baffin Bay over the past decades, this conjecture still remains unproven, mostly due to the absence of adequate hydrographic data obtained from relevant locations. Attempting to address this question necessitates year-long sampling of the denser waters of Smith Sound from which we can characterize the variability of hydrographic properties and velocity of the bottom waters. Smith Sound has a complex bathymetry. If dense waters are produced during polynya events on the shallow Greenland shelves, it is likely that these waters would sink along the slopes and fill intermediate if not bottom waters of the 1000 m deep canyon, or into the centre main channel of Smith Sound, and reach the Baffin Bay basin passing through the channel's southern end. By measuring hydrographic water properties and current velocities at this strategic location would allow us 1) to determine whether Smith Sound is a source of Baffin Bay deep and bottom waters, 2) to determine the origin of these waters and 3) to characterize the variability of the transport. Such information is particularly important for constraining mass and heat budgets as well as determining pathways of nutrients, contaminants and other biogeochemical tracers. It would greatly help validate and constrain circulation models, which are being developed as tools for scientific discovery but also for ecosystem management (Arc3Bio ArcticNet Project and Dumont's Discovery Grant).

The strategic goals of the renewed Long-Term Oceanic Observatories project (LTOO) during the last phase of ArcticNet (2015-2018) are (1) to maintain the deployment of LTOO during the last phase of ArcticNet and beyond; (2) to coordinate ArcticNet's ongoing LTOO program with the new integrated Beaufort Observatory (iBO) in the Beaufort Sea and with the GreenEdge project in Baffin Bay; (3) to further exploit the material and data recorded by the LTOO since 2002 to investigate decadal changes in circulation and ice regime, and their impacts on ecosystem function in the Beaufort Sea; (4) to investigate and model the formation of deep waters in northern Baffin Bay; (5) to connect the LTOO project to similar observatories in the Fram Strait, Chukchi Sea and Queen Maud Gulf through ongoing collaborations with, AWI, AOOS, the W. Garfield Weston Foundation, and Parks Canada.

ACTIVITIES

Objective 1- Continuation/expansion of LTOO in Canadian and international waters

- Six moorings including seven sediment traps and two hydrophones were recovered and redeployed jointly by ArcticNet-LTOO and the iBO initiative in the Beaufort Sea on board the CCGS *Amundsen* in summer 2016. A mooring engineer (Shawn Meredyk) coordinated the recovery, calibration and redeployment of moored instruments on board the CCGS *Amundsen*.

- The sequential sediment trap deployed on the Chukchi Ecosystem Mooring on the northern Chukchi shelf in August 2015 was successfully recovered on board the USCGS *Healy* in August 2016 and redeployed for an additional year of sampling. Samples were received at the laboratory at Université Laval in August and measurements of chlorophyll a, particulate organic carbon, total particulate matter, zooplankton fecal pellets, and phytoplankton cells, as well as swimmer (zooplankton) identification, will be completed by March 2017. A manuscript on these results is in preparation.
- An additional sequential sediment trap that was deployed in July 2015 as part of the Queen Maud Gulf-Victoria Strait marine ecosystem pilot study was recovered in 2016 and redeployed for 2016-2017. The pilot study initiated in 2015 has now evolved in a 3-year project (Kitikmeot Marine Ecosystems Study). Samples are currently being processed.
- Marie Parenteau, research assistant conducting microscopic identifications of phytoplankton cells on sediment trap samples at Université Laval, traveled once again this year to the Alfred-Wegener Institute in Germany in November 2016 for a 1-week phytoplankton identification internship with Dr. Eva-Maria Nöthig. While in Germany, she completed the identification of samples collected in sediment traps deployed by the AWI in the Siberian Arctic. These results are included in a manuscript to be submitted in the coming weeks entitled 'Multiannual trends in ice algae and phytoplankton export in the Siberian Arctic Ocean'
- Gabrielle Nadaï, a B.Sc. student who obtained NSERC summer grants in the laboratory of Louis Fortier in 2015 and 2016, applied for a M.Sc. NSERC grant to study the impact of an early sea ice retreat on the pelagic ecosystem of the Beaufort Sea as a contribution to LTOO.

Objective 2 - Year-round monitoring of pelagic ecosystem function from 2002 to 2018 in the Beaufort Sea: a synthesis

- Processing of the sediment trap samples recovered in the Beaufort Sea in 2016 started at Université Laval in September with the microscopic identification of phytoplankton cells. Additional analyses (splitting + removal and identification of swimmers before measurements of weight, carbon and nitrogen) are ongoing and should be completed before summer.
- Microscopic identifications of the phytoplankton cells of the historical sediment trap samples collected earlier during the LTOO project are still ongoing as part of the long-term monitoring of the pelagic ecosystem function in the Beaufort Sea. At the moment, 25% of the microscopic analyses on all samples available have been completed
- Thibaud Dezutter presented his M.Sc. seminar in November and will complete his M.Sc. thesis entitled 'Warmer conditions and the match-mismatch between phytoplankton and zooplankton in the Beaufort Sea: a multiannual study' under the supervision of Dr. Louis Fortier during the winter 2017 semester. The objective of the thesis within the framework of the LTOO project was to investigate the match-mismatch between phytoplankton and zooplankton under different physical conditions using phytoplankton and swimmers collected over a 5-year period at the Beaufort Sea shelf break. The thesis was written in the form of a scientific paper and will be submitted in the coming weeks to the journal Global Change Biology.
- Thibaud Dezutter completed a course on Arctic marine zooplankton from August 12 to September 16 at the University Centre in Svalbard (UNIS) partly funded by ArcticNet and Québec-Océan.

- Subsamples were sent in May to Dr. Vera Pospelova at the University of Victoria for dinoflagellate cyst analyses on sediment trap samples collected in 2014-2015 in the Beaufort Sea (BR-G B). This collaborative project has the goal to document composition, diversity, abundance and seasonal successions of dinoflagellate cyst species, including toxic and potentially toxic species of dinoflagellates, and to examine these parameters in relation to changes in ice cover, sea surface temperature, and salinity. Establishing seasonal and inter-annual trends of cyst-producing dinoflagellates and identifying their geographical patterns will allow tuning cyst method for high-resolution proxy-based paleo-reconstructions in the Arctic waters.
- Together with CREG12 model results, data obtained as part of LTOO were used by postdoctoral fellow Christiane Dufresne to describe the interannual and regional variability of oceanographic patterns (global, regional, mesoscale) in the eastern Beaufort Sea. LTOO observations provided essential data for the validation of numerical models. The very high frequency of recorded data allowed a good description of local processes, often short in duration and difficult to reproduce by models. In the Beaufort Sea, LTOO data highlighted a slight overestimation of temperatures and surface salinity modeled with the CREG12 model (CMC-Environment Canada), but the model reproduced with satisfying accuracy and reliability major surface patterns. Despite its bias, the model helped to understand both spatial and temporal variations and revealed variability patterns in sea surface salinity and temperature, ice thickness and mixed layer depth.
- Thibaud Dezutter, Igor Dmitrenko, Christiane Dufresne, Alexandre Forest, Sergei Kirillov, and Catherine Lalande presented results obtained as part of the LTOO project at the ArcticNet Annual Scientific Meeting in Winnipeg in December 2016. Christiane Dufresne will also present a talk including LTOO results at the ASLO Aquatic Sciences Meeting in Honolulu in February 2017.

Objective 3 - Formation of the North Water and the ice edge in Baffin Bay

- Ice-anchored sequential sediment traps were deployed as a LTOO contribution to the Green Edge project at an ice camp near Qikiqtarjuaq on Broughton Island (Baffin Bay) from May to July 2016. A drifting sediment trap was also deployed and recovered from the CCGS *Amundsen* from June to July 2016 as part of Green Edge. All sediment trap samples were analyzed for measurements of chlorophyll a, particulate organic carbon, total particulate matter, zooplankton fecal pellets, phytoplankton cells and swimmer (zooplankton) identification. Gabrielle Nadaï, an undergraduate student who was awarded an Undergraduate Student Research Award by the Natural Sciences and Engineering Research Council of Canada in 2015, obtained a second Undergraduate Student Research Award in 2016, and has once again done these analyses during summer 2016. Marie Parenteau, a research assistant supported by the LTOO project, has completed all the phytoplankton identification for the Green Edge project during summer 2016. Preliminary results were presented by Catherine Lalande at the GreenEdge annual workshop held in Nice, France in December 2016.
- Essi Enyonam Aboyo passed her doctoral exam and will present her Ph.D. project seminar entitled 'Dynamics of formation and transformation of water masses in Baffin Bay' in the coming weeks. The main objective of her Ph.D. project is to quantify the formation of dense waters through modelling and using the LTOO data.
- In an attempt to determine the source of deep waters in Baffin Bay, annual sampling of the denser waters of Smith Sound is required to characterize the variability of hydrographic properties and velocity of the bottom waters. The deployment of oceanographic moorings measuring hydrographic water properties and current velocities at a strategic location in Baffin

Bay will allow to 1) determine whether Smith Sound is a source of Baffin Bay deep and bottom waters, 2) determine the origin of these waters and 3) characterize the variability of the transport. Two moorings were deployed in northern Baffin Bay in 2016 and will be recovered and redeployed in 2017.

RESULTS

The following section includes results obtained and presented in the second year of ArcticNet's phase 4 (2016-2017) as well as results obtained during the previous phases of the Long-Term Oceanic Observatories project that are in preparation for publication.

Warmer conditions and the match-mismatch between phytoplankton and zooplankton in the Beaufort Sea: a multiannual study (Dezutter, Lalande, Dufresne, Parenteau, Fortier)

As part of ArcticNet's Long-Term Oceanic Observatories (LTOO) project, moored sediment traps have been deployed at the Beaufort Sea shelf break since 2003 to monitor the downward flux of biogenic matter. Here, we use phytoplankton cells and zooplankton (swimmers) collected in sediment trap samples from 2009 to 2015 to investigate the match or mismatch between primary production and the vernal migration of zooplankton from winter depths to the surface layer. Interannual differences in timing between the phytoplankton bloom and the migration of copepods were investigated in function of water temperature from current meters deployed on the same moorings, as well as satellite-derived sea ice concentration and snow depth. The occurrence of the key copepod *Calanus glacialis* was associated with peaks in abundance of the true ice-algae *Nitzschia frigida*, while *Calanus hyperboreus* and their nauplii were associated with peaks in diatom abundances. In most years sampled, *C. glacialis* arrived ~15 days before the export of *N. frigida*, while *C. hyperboreus* nauplii coincided with peaks in diatom fluxes (Figure 1). However, an unusually warm upper water column in fall 2012 and winter/spring 2013 accompanied with late snow melt and sea ice breakup delayed the export of *N. frigida* and resulted in *C. glacialis* arriving ~90 days earlier than the export of ice algae (Figure 1). A ~90 days delay was also observed between *C. hyperboreus* nauplii and the peak in diatom fluxes (Figure 2). As ice algae and phytoplankton are essential food source for the reproduction and development of *Calanus copepods*, those mismatch events likely have negative impact on their recruitment and on the transfer of energy within the Arctic food-web.

Spatial and temporal variability in phytoplankton and particulate matter export in the Beaufort Sea (2014-2015) (Lalande, Parenteau, Fortier)

The integrated Beaufort Observatory (iBO) is a 4-year mooring program (2015-2018) targeting the shelf and slope environment of the Canadian Beaufort Sea. The project, co-led by ArcticNet, the Institute of Ocean Sciences (Department of Fisheries and Oceans Canada, DFO), Université Laval, and Golder Associates, and supported by the Environmental Studies Research Funds (ESRF) and Imperial Oil Limited, aims to extend existing time-series and regional coverage. As part of the iBO project, seven sequential sediment traps were deployed on five mooring lines located along the Mackenzie shelf break and west of Banks Island for the measurement of biogeochemical fluxes from September 2014 to August 2015. We present the export fluxes of total particulate matter (TPM), particulate organic carbon (POC), and phytoplankton cells at these five sites. Whereas most TPM and POC fluxes measured at the Mackenzie shelf break were in a similar range, two very large peaks in TPM and POC fluxes were observed at the shallowest site on the shelf in November and March, likely due to resuspension caused by a change in current direction. TPM and POC fluxes measured at the site west of Banks Island were minimal. Phytoplankton cells collected in the sediment traps, nearly all diatoms, reflect the magnitude, timing, and duration of the phytoplankton bloom in the Beaufort Sea. Diatom fluxes started to increase at the end of April and peaked at the end of May/ beginning of June at the Mackenzie shelf break, while they increased in June and peaked in August west of Banks Island. Diatoms fluxes were highest at the two shallowest sites at the Mackenzie shelf break and very low west of Banks Island. Contrasting fluxes between a heavy ice year (2014-2015, above) and an ice-poor year (2015-2016) will contribute to our understanding of the present and future state of the Beaufort Sea.

Annual cycle of biogenic matter export on the Chukchi Sea continental shelf (Lalande, Grebmeier, Parenteau, Fortier, Danielson)

Preliminary results show that export fluxes measured on the Chukchi Sea continental shelf from August 2015 to July 2016 clearly showed twop very large peaks of phytoplankton production and export during the deployment year (Figure 3). First, very large phytoplankton export was recorded in September and October 2015, at a time when there was a high frequency of storms in the area. Phytoplankton fluxes decreased in November and were relatively low from December to May. The ice algae *Nitzschia frigida* was observed in the sediment trap in May and June. *Nitzschia frigida* was likely released from the ice when snow melt was initiated, suggesting at least two snow melt events before ice retreated in the region (Figure 3). Phytoplankton export then drastically increased at the end of June and remained very high for the month of July, at the end of which the sediment trap was recovered. Phytoplankton export fluxes were as high during Fall 2015 than during Summer 2016, underscoring the tremendous importance of fall blooms for the annual production

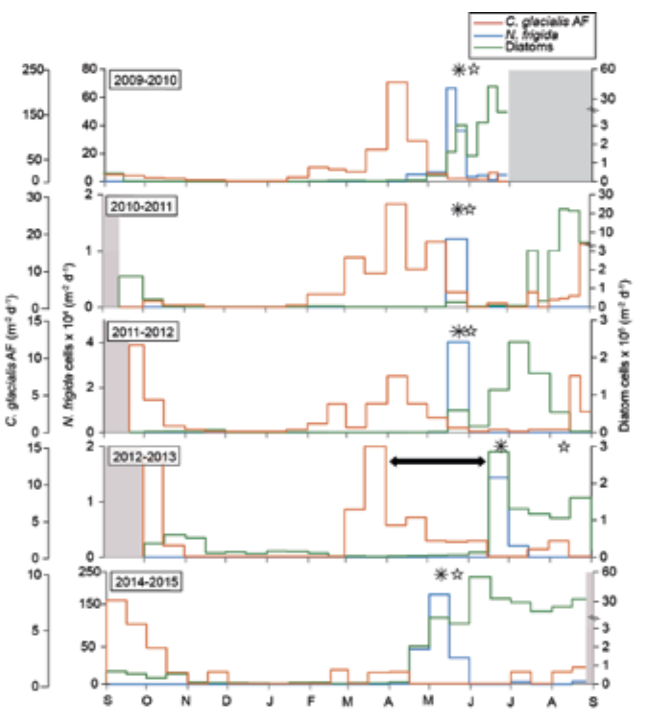

Figure 1. Difference in timing between the vernal migration of Calanus glacialis female, Nitzschia frigida export (blue) and diatom export (green) at ~100 m for the five deployment years. The black arrow indicates the mismatch event. Grey zones indicate period with no data. Black stars indicate the onset of snow melt and white stars indicate periods of sea ice break-up. Note different scales.

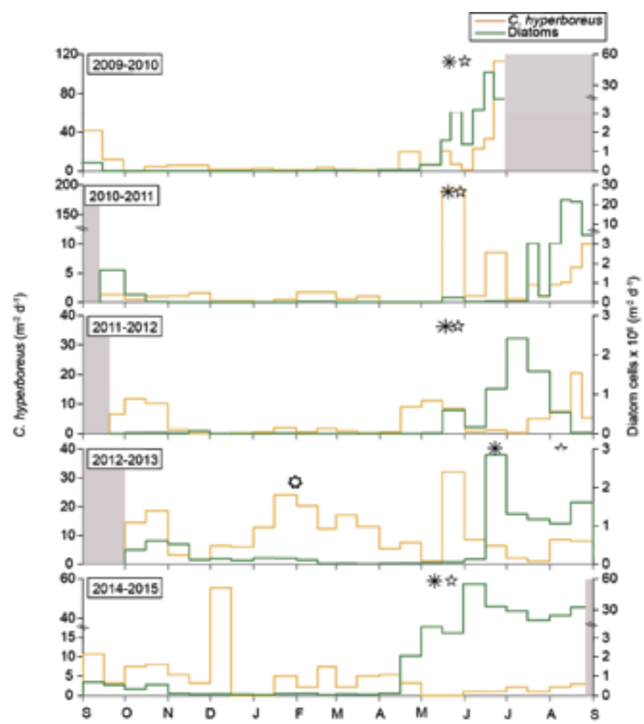

Figure 2. Difference in timing between the vernal migration of Calanus hyperboreus (yellow) and diatom export (green) at ~100 m for the five deployment years. Grey zones indicate periods with no data. The large white star indicates the early upward migration event; black stars indicates the onset of snow melt; small white stars indicate periods of sea ice break-up. Note different scales.

in the Chukchi Sea ecosystem. The proportion of dead diatom cells (without cell content) collected was larger than living cells (with cell content) during October, possibly reflecting the resuspension of settled phytoplankton cells.

Multiannual trends in ice algae and phytoplankton export in the Siberian Arctic Ocean (Lalande, Nöthig, Bauerfeind, Krumpen, Parenteau, Fortier)

A large increase in annual primary productivity following a considerable loss of summer sea ice has recently been reported for the Siberian sector of the Arctic Ocean. The scarcity of field data to corroborate these satellite-derived observations incited a collaborative international study combining six years of sequential sediment trap measurements obtained over a 17-year period in the Siberian Arctic Ocean. Here we show that export fluxes measured at ~300 m reflect progressively earlier ice algae export under warmer conditions, whereas the magnitude of diatom fluxes were similar under reduced ice cover and enhanced carbon fluxes reflected the release of particles from melting ice.

Under-ice export fluxes of biogenic matter in Baffin Bay (Lalande and Fortier)

Sequential sediment traps were deployed at 25 and 100 m under-ice from May 15 to July 19 2016 during the Green Edge ice camp in Baffin Bay, and from June 15 to July 9 2016 during the CCGS *Amundsen* in Baffin Bay. Measurements of total particulate matter (TPM), chlorophyll a (Chl a), particulate organic carbon (POC), phytoplankton cells, swimmers, and zooplankton fecal pellets have been performed on the trap samples. These results, along with the results obtained at the ice camp in 2015, will be presented in a manuscript currently in preparation.

The integrated Beaufort Observatory (iBO) (Forest, Melling, Lalande, Lévesque, Merzouk, Meredyk, Michaud, Osborne)

The integrated Beaufort Observatory (iBO) is a four-year mooring program (2015-2018) targeting the shelf and slope environment of the Canadian Beaufort Sea

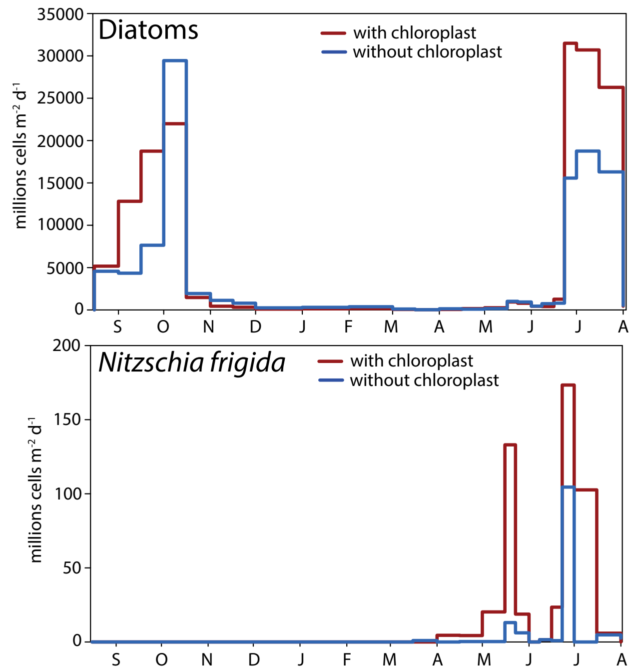

Figure 3. Diatom and ice algae (Nitzschia frigida) export fluxes collected from August 2015 to July 2016 on the Chukchi Sea continental shelf.

and co-led by ArcticNet, the Institute of Ocean Sciences (Department of Fisheries and Oceans Canada, DFO), Université Laval, and Golder Associates. The program is supported by the Environmental Studies Research Funds (ESRF) and Imperial Oil Limited and aims to extend existing time-series and regional coverage and contribute key information required for decisions on oil and gas development and regulations in the offshore Beaufort Sea. The iBO sampling array is composed of seven tautline moorings located in waters ranging from 20 to 750 m depth at key locations from the Mackenzie Canyon, to the mid- and outer central shelf and slope, up to the remote area near Banks Island. The moorings are equipped with state-of-the-art instrumentation, including acoustic Doppler current profilers for current speed and direction, ice drift and plankton/particulate matter backscattering; ice-profiling sonars for sea ice thickness, under-ice topography, and waves; water property loggers for salinity, temperature, turbidity and chlorophyll; and automated sediment traps for the measurement of biogeochemical fluxes. In addition, iBO builds upon extensive time-series acquired by DFO since the 1980's and through ArcticNet and related projects from 2002 to 2015 (e.g. Canadian Arctic Shelf Exchange Study, Industry partnership, Beaufort Regional Environmental Assessment). With the collection of multi-year observations and the integration of historical datasets, iBO will contribute to the regional syntheses of ocean circulation, sea ice observations and biogeochemical fluxes that will include: (1) information on the magnitude, duration and return period of extreme ice features and ocean currents, comprising those associated with mesoscale eddies and storm surges; (2) key datasets to assess sea ice and seawater trajectories and particulate matter fluxes across key areas over the shelf and slope in relation to various transport mechanisms, such as upwelling and downwelling; and (3) data to support accurate predictive capability and the validation/verification of regional circulation, ice drift models, and oil spill trajectories. Consolidating historical datasets with the knowledge generated through the iBO program will provide the basis for the production of a State of the Beaufort Sea Report.

Observations and numerical modelling reveal recent seasonal and inter-annual patterns in the oceanography of the Eastern Beaufort Sea (Canadian Arctic) (Dufresne, Maps, Dupont, Fortier)

The receding sea-ice cover in the Arctic Ocean will inevitably lead to drastic changes in the timing and fate of the planktonic primary production at the base of the whole marine food-web. Changes in light and nutrient availability or water masses stratification are some of the many physical processes linked to the sea ice dynamics that directly influence phytoplankton productivity. In this rapidly changing ocean, a comprehensive understanding of the dynamics of such physical processes is essential to describe and eventually predict the fate of the marine primary production. In this study, we described the inter-annual and seasonal variability of the major physical processes controlling phytoplankton production in the eastern Beaufort Sea and Amundsen Gulf: sea surface temperature (SST), sea surface salinity (SSS) and sea-ice thickness (SIT), using observations and model results. The CREG12 model configuration is developed by CONCEPTS (Canadian Operational Network of Coupled Environmental PredicTion Systems) and is operationally used to forecast the sea ice dynamics. It is based on the NEMO framework and its numerical domain covers the entire Arctic Ocean and the North Atlantic Ocean. We focused our study on the eastern Beaufort Sea and Amundsen Gulf since this area has been studied for almost 12 years, as part of the ArcticNet project Long-Term Oceanic Observatories (LTOO). Long-term moorings have been deployed along the continental shelf at different depths and recorded temperature and salinity for many complete seasonal cycles. We used these extensive datasets to test the model accuracy. A first comparison between computed output and observed data showed that the model reproduced with satisfying accuracy and reliability the major surface patterns in temperature and salinity (Figure 4). While some short-term and localized processes are not simulated, the major features of the different water masses dynamics are computed adequately. For example, on the continental slope, major upwelling events are represented. For the six moorings analyzed in this study, statistical analyses showed significant agreement between output and data. Autumn months usually showed the largest differences between modeled output and observed data, owing to the use of a climatological forcing for the Mackenzie River freshwater discharge and the complex dynamics of wind-induced upwelling. After assessing the representation of surface water masses in the area of interest, simulated output was then used to describe their inter-annual and regional variability. We revealed the dominant modes of variability of the sea surface temperature (SST) and salinity (SSS) as well as sea-ice thickness (SIT) by using empirical orthogonal function (EOF) analysis on the CREG12 output. EOFs allow the identification of several independent spatial modes of variability in conjunction with their temporal dynamics. The first mode of variability of SST, SSS and SIT was largely dominated by seasonality, as expected. The second and third modes showed that the southern part of the domain is the more variable and is strongly conditioned by the coast morphology and bathymetry. This variability highlights the influence of remote winter storms on the strength and direction of the Alaskan Coastal Current and the dispersion of the Mackenzie plume.

Wind-forced water dynamics over the Eastern Beaufort Sea continental slope (Dmitrenko, Kirillov, Forest, Barber)

The shelfbreak currents over the Beaufort Sea continental slope are known to be one of the most energetic features of the Beaufort Sea hydrography. The oceanographic mooring CA13-03 deployed over the Canadian (eastern) Beaufort Sea continental slope in October 2003 recorded current velocity over two consecutive years until June 2005. Data analysis revealed that the downwelling favorable local wind forcing usually associated with cyclones passing north of the Beaufort Sea continental slope toward the Canadian Archipelago generates bottom intensified shelfbreak currents with along-slope eastward flow up to 120 cm/s. These cyclones also generate storm surges along the Beaufort Sea coast with sea surface height (SHH) rising up to 1.4 m following the westerly wind maxima. The westerly along-slope wind also generates a surface Ekman onshore transport. The associated SSH increase over the shelf produces a cross-slope pressure gradient that drives an along-slope eastward geostrophic current, in the same direction as the wind. This wind-driven barotropic flow is superimposed on the background baroclinic bottom-intensified shelfbreak current that consequently amplified. In contrast, the surface intensified currents with along-slope westward flow are observed in response to the upwelling favorable wind forcing usually associated with Pacific-born cyclones passing south of the Beaufort Sea coast. The upwelling favorable easterly winds generate a surface Ekman transport that moves surface waters offshore. The associated cross-slope pressure gradient drives an along-slope westward barotropic flow that is superimposed on the background eastward transport resulting in surface intensified shelfbreak flow.

Fall upwelling events in the Canadian Beaufort Sea: atmospheric drivers, shelf-slope circulation and sediment resuspension (Forest, Osborne, Melling, Dmitrenko, Fortier, Curtiss, Lowings)

Fall upwelling is a key process of the Arctic continental shelf that allows the seasonal exchange of brackish and nutrient-poor shelf waters with dense and nutrient-rich

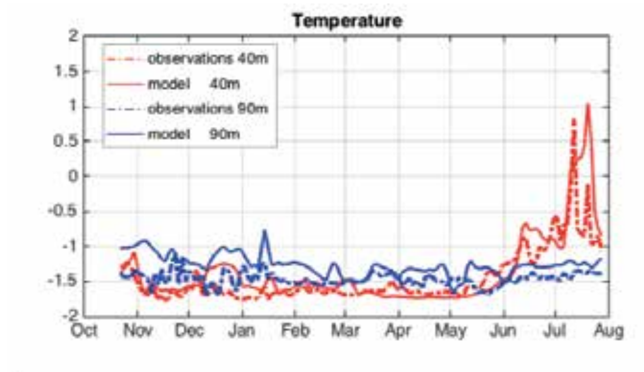

Figure 4. Modeled output (plain line) and observed (dash line) temperatures at 40 m (red) and 90 m (blue) at CA04 from October 2007 to August 2008.

waters from the deep offshore environment. Here, we combine measurements from an extensive mooring array deployed in the Canadian Beaufort Sea in autumn 2014 with remote sensing observations and reanalysis data to investigate synoptically the dynamics of this process. We seek to understand the role of atmospheric pressure systems, wind and sea ice motion in driving water mass distributions and ocean current variability during successive upwelling episodes and explore the implications with respect to increases in near-bottom suspended sediment concentrations (SSC) associated with energetic along-slope flows. The sequence of events in fall 2014 initiated when a marked frontal system with low sea level pressure over the Northeast Pacific and high pressure over the Arctic Ocean developed in October and generated upwelling-favorable winds from the ENE in the Beaufort Sea. As a result: (1) shelf waters with mean salinity ≈ 31.5 moved offshore and were progressively replaced with Upper Halocline waters at ~32.5; (2) a marked negative sea level anomaly (>30 cm) was detected on the inner shelf; and (3) high-velocity currents to the SW (up to 50 cm s^{-1}) developed near the shelf break (~80 m depth) in the opposite direction to the mean circulation. When the winds faded in late October, currents near the shelf break veered back to the NE and a strong jet (~60 cm s^{-1}) trapped on the upper slope developed in response to upwelling relaxation. The latter induced a short-lived intrusion of Atlantic Water (salinity = 34.7) typically found at 240 m onto the outer shelf. While weak winds prevailed in November-December, shelf waters further increased in salinity from ~32.5 to ~33.0 due to upwelling apparently forced by longshore stress imposed by the growing ice cover moving anti-cyclonically under the persistent high-pressure system. Reversal of the mean shelf-break circulation with stronger currents to the SW followed by a slope-trapped jet to the NE associated with upwelling relaxation were again identified during this period. Peaks in near-bottom SSC (up to 40 g m^{-3}) attributed to local seabed erosion were recorded on the upper slope during periods of both increased SW and NE shelf-break currents. However, the response was spatially different with the Mackenzie Canyon reacting specifically to the up-shelf flows to the SW and the outer central Mackenzie Shelf responding more intensely to the relaxation counter-flows to the NE. By contrast, no clear response in current speed and SSC was observed in the vicinity of the Banks Island shelf. Our results provide a detailed characterization of upwelling dynamics in the Canadian Beaufort Sea based on integration of high-resolution data and underscore the need to monitor shelf-slope exchange processes in the region to better understand their impact on ocean circulation and biogeochemical fluxes under shifting meteorological and sea ice conditions.

Upwelling of Atlantic Water along the Canadian Beaufort Sea continental slope: Favorable atmospheric conditions and seasonal and interannual variations (Kirillov, Dmitrenko, Tremblay, Gratton, Barber, Rysgaard)

The role of wind forcing on the vertical displacement of the -1C isotherm and 33.8 isohaline depths was examined based on snapshots of historical (1950–2013) temperature and salinity profiles along the Mackenzie continental slope (Beaufort Sea). It is found that upwelling is correlated with along-slope northeast (T59) winds during both ice-free and ice-covered conditions, although the wind impact is more efficient during the ice-free season. One of the most important factors responsible for vertical displacements of isopycnals is sustained wind forcing that can last for several weeks and even longer. It accounts for 14–55% of total variance in isotherm/isohaline depths, although these numbers might be underestimated. The upwelling and downwelling events are discussed in the context of the interplay between two regional centers of action - the Beaufort high and Aleutian low - that control the wind pattern over the southern Beaufort Sea. The probability of upwelling-favorable wind occurrence is closely related to the sea level pressure difference between these two centers, as well as their geographical positions. The combined effect of both centers expressed as the SLP differences is highly correlated (0.68/0.66 for summer/winter) with occurrences of extreme upwelling favorable northeast (NE) winds over the Mackenzie slope, although the Beaufort high plays a more important role. The authors also diagnosed the predominant upwelling-favorable conditions over the Mackenzie slope in the recent decade associated with the summertime amplification of the Beaufort high. The upwelling favorable NE wind occurrences also demonstrate the significant but low (-0.30) correlation with Arctic Oscillation (AO) during both summer and winter seasons, whereas the high correlation with North Pacific index (NPI; -0.52) is obtained only for the ice-covered period.

Dinoflagellate cyst production over an annual cycle in seasonally ice-covered Hudson Bay (Heikkilä, Pospelova, Forest, Stern, Fortier, Macdonald)

We present continuous bi-weekly to bi-monthly dinoflagellate cyst, tintinnid loricae and tintinnid cyst fluxes at two mooring sites in Hudson Bay (subarctic Canada) from October 2005 to September 2006. The total dinoflagellate cyst fluxes at the site on the western side of the bay ranged from 4600 to 53,600 cysts m^{-2} day^{-1} (average 20,000 cysts m^{-2} day^{-1}), while on average three times higher fluxes (average 62,300 cysts m^{-2} day^{-1}) were recorded at the site on the eastern side of the bay with a range from 2700 to 394,800 cysts m^{-2} day^{-1}. These values are equivalent to the average fluxes calculated from the top 1-cm sediment layer of ^{210}Pb-dated box cores at corresponding locations, and hence lend support to the use of sediment dinoflagellate cysts in palaeoceanography. Tintinnid fluxes ranged from 1200 to 80,000 specimens m^{-2} day^{-1} (average 32,100 tintinnids m^{-2} day^{-1}) in the west, and 1600 to 1,240,800 specimens m^{-2} day^{-1} (average 106,800 tintinnids m^{-2} day^{-1}) in the east, with the highest *Salpingella* sp. fluxes recorded during the sea-ice cover season.

The dinoflagellate cyst species diversity recorded in the traps was similar at the two environmentally differing locations, with cold-water (e.g., *Echinidinium karaense*, *Islandinium minutum*, *Islandinium cezare*, *Polykrikos* sp. var. *arctica, Spiniferites elongatus*), cosmopolitan (e.g., *Operculodinium centrocarpum, Spiniferites ramosus, Brigantedinium*) and typical warmer-water (e.g., *Echinidinium aculeatum, Islanidium brevispinosum*) species present. Furthermore, the species-specific timing of cyst production behaved similarly relative to the seasonal sea-ice cycle at both locations. Cyst species proportions and species-specific flux quantities, however, differed between the two sites and corresponded to the quantities and species assemblages recorded in the surface sediment, with the exception of cysts of *Polarella glacialis* and cf. *Biecheleria* sp. that seem not to preserve well in sediment but were abundant in both traps. Otherwise, cyst assemblage at the western trap site was dominated by *O. centrocarpum* and *S. elongatus* while at the eastern site very high quantities of cysts of *Pentapharsodinium dalei* were recorded. Our data do not lend support to the hypothesis that trophic status solely determines whether cyst production takes place under-ice or in the open water, since cysts of light-dependent (phototrophic) and light-independent (heterotrophic) dinoflagellates are recorded during both conditions. Most importantly, negligible under-ice cyst production is recorded during the deep arctic winter.

Current surges and seabed erosion near the shelf break in the Canadian Beaufort Sea: A response to wind and ice motion stress (Forest, Osborne, Curtiss, Lowings)

Estimating the erosion potential of seabed sediments and the magnitude of the resulting suspended load in relation to current dynamics near the shelf break is a key issue for better understanding shelf-slope sediment transport. On the outer Mackenzie Shelf (Canadian Beaufort Sea, Arctic Ocean), a thin and discontinuous veneer of recent surficial clays overlie old glaciomarine sediments that further pinch out at the shelf edge. Gas and fluid venting is known to underlie part of sediment instability in the area, but recent mooring-based measurements also indicate that sediments near the shelf break are recurrently remobilized by strong subsurface currents. Here, we relate storms to the development of current surges that resulted in the abrupt resuspension of sediments at two locations along the shelf break. Near-bottom concentrations of suspended sediments were estimated using the acoustic backscatter of high-frequency acoustic Doppler current profilers deployed from September 2011 to September 2013 as part of the Beaufort Regional Environmental Assessment (BREA) program. Near-bottom currents near the shelf edge (140 to 150 m isobaths) were characterized by recurring episodes of elevated velocities (instantaneous speeds up to ~ 40-50 cm s^{-1}) that were extensions of current surges (~ 60-80 cm s^{-1}) occurring in the core of the shelfbreak jet located at ca. 90-120 m. Sudden peaks in suspended sediments (above 100 g m^{-3}) corresponded closely with current surges in the near-bottom boundary layer (<10 m) implying the local erosion of surficial sediments and the rapid advection or redeposition of the resuspended sediments. A range of apparent threshold velocities from 18 to 36 cm s^{-1} was calculated based on the relationship between suspended sediment concentrations and near-bottom current speeds. Two meteorological scenarios were identified to explain the current surges underlying these erosion events at the shelf edge: (1) Pacific or Arctic-born low pressure systems that propagate into the southern Beaufort Sea and are associated with intense downwelling-favorable westerly winds. These amplify the eastward-setting shelfbreak jet along the upper slope, such as in September 2012 when successive cyclones developed during the record-low sea ice extent. (2) The persistence of a high-pressure system over the Beaufort Sea that causes strong upwelling-favorable easterly winds and a strengthening of anti-cyclonic ice motion. This induces a reversal of the shelfbreak jet to the west and a subsequent eastward-directed relaxation flow when the winds fade, such as during the major ice fracturing events of January to March 2013 that were associated with strong and persistent current speeds.

Shelfbreak current over the Canadian Beaufort Sea continental slope: Wind-driven events in January 2005 (Dmitrenko, Kirillov, Forest, Gratton, Volkov, Williams, Lukovich, Bélanger, Barber)

The shelfbreak current over the Beaufort Sea continental slope is known to be one of the most energetic features of the Beaufort Sea hydrography. In January 2005, three oceanographic moorings deployed over the Canadian (eastern) Beaufort Sea continental slope simultaneously recorded two consecutive shelfbreak current events with along-slope eastward bottom-intensified flow up to 120 cm s^{-1}. Both events were generated by the local wind forcing associated with two Pacific-born cyclones passing north of the Beaufort Sea continental slope toward the Canadian Archipelago. Over the mooring array, the associated westerly wind exceeded 15 m s^{-1}. These two cyclones generated storm surges along the Beaufort Sea coast with sea surface height (SSH) rising up to 1.4 m following the two westerly wind maxima. We suggest that the westerly along-slope wind generated a surface Ekman onshore transport. The associated SSH increase over the shelf produced a cross-slope pressure gradient that drove an along-slope eastward geostrophic current, in the same direction as the wind. This wind-driven barotropic flow was superimposed on the background baroclinic bottom-intensified shelfbreak current that consequently amplified. Summer-fall satellite altimetry data for 1992–2013 show that the SSH gradient in the southeastern Beaufort Sea is enhanced over the upper continental slope in response to frequent storm surge events. Because the local wind forcing and/or sea-ice drift could not explain the reduction of sea-ice concentration over the Beaufort Sea continental slope in January 2005, we speculate that wind-driven sea level fluctuations may impact the sea-ice cover in winter.

Sediment Dynamics from Coast to Slope – Southern Canadian Beaufort Sea (Osborne and Forest)

Profound changes in cross-shelf sediment fluxes are anticipated in coming decades in the southern Canadian Beaufort Sea where an accelerated increase in temperature could lead to large changes in Arctic river hydrology and coastal-marine geomorphologic processes. In the past decade sediment exported to the Beaufort Shelf has increased while sea level pressure has increased accelerating the Beaufort Gyre, strengthening coastal upwelling and expanding the Mackenzie River plume offshore. Sea-ice extent has decreased while storminess has increased increasing wave action, coastal downwelling, current surge and resuspension and transport on the shoreface and shelf. This paper investigates mechanisms, quantities and rates of sediment transport operating in this cold continental shelf-slope environment. Past studies from more than two decades of research are compared with recent measurements to develop improved estimates of sediment sources, pathways, fate and fluxes across the shelf and slope. In particular, we explore connections between data from a long term mooring observatory deployed over the continental shelf and slope during the ArcticNet-Industry Partnership (2009–2011) and Beaufort Regional Environmental Assessment (BREA 2011–2015) to those acquired in studies focusing on nearshore and shoreface. Sediment fluxes from the Mackenzie River and erosion of permafrost coasts are compared with outer shelf-slope measurements of settling particles and near-bottom fluxes. In turn, the role of atmospheric and cryospheric processes in forcing sediment transfer from coast to slope is investigated to assess system response to changing climate and evaluate implications for marine hydrocarbon resource development along the continental margin of the Arctic Ocean.

DISCUSSION

In the Beaufort Sea, the record low ice cover extent of 2012 led to increased solar absorption in surface waters during the summer months and until the end of October (Babb et al., 2016). An important reversal in current direction in October 2012 may have contributed to the formation of a near surface temperature maxima, which trapped warm water under the halocline during the following winter (Jackson et al., 2010), explaining the warm water temperature observed at ~50 m from November 2012 to June 2013 at the BR-G mooring. The record low ice cover of 2012 was followed by a quick recovery of the ice extent during the following summer (Liu and Key, 2014), resulting in a late sea ice break-up in 2013.

The combination of warm water temperature and late ice break-up in 2013 disrupted the usual match between primary producers and the vernal migration of herbivorous copepods. In the highly seasonal Arctic Ocean, the vernal migration of C. glacialis typically matches the onset of ice algae growth, allowing adult females (AF) to feed on ice algae for maturation and early egg production, and/or to enhance the development of copepodite stages C3-C4 into C5-AF (Tourangeau and Runge, 1991; Søreide et al., 2010; Wold et al., 2011). For all years sampled except 2013, the upward migration of *C. glacialis* preceded the export of the ice algae *N. frigida* by six to eight weeks (Figure 1). However, due to the late snow melt and ice break-up in 2013, the peak in *N. frigida* export was observed in late June, 13 to 15 weeks following the upward migration of *C. glacialis* at the end of March, causing a mismatch between zooplankton and phytoplankton (Figure 1). The delayed export of *N. frigida* created an overlap with the export of pelagic phytoplankton when snow abruptly melted, with a potentially negative effect on *C. glacialis* recruitment. Usually, the delay between the release of ice algae and pelagic phytoplankton production provides sufficient time for nauplii to develop into their first feeding stage (N3) and subsequently feed on pelagic production. The overlap between ice algae release and phytoplankton export in 2013 likely led to the development of nauplii into their feeding stages at the end of the pelagic bloom only. Leu et al. (2011) observed a similar situation in Svalbard when a late sea ice break-up reduced the time lag between the peaks of ice algae and pelagic phytoplankton production, resulting in a lower biomass and abundance of *C. glacialis* that year.

With the ongoing warming of the Arctic Ocean, late sea ice break-up events will likely become increasingly rare and the situation observed here is therefore particular in a context of climate change. On the other hand, as sea ice becomes thinner, more scattered and more dynamic, ice may drift and accumulate in regions that were otherwise ice free and could affect the spring bloom phenology.

The impacts of an early ice break-up on the timing between ice algae/phytoplankton production and zooplankton recruitment were investigated in a Svalbard fjord and in the Amundsen Gulf by Søreide et al. (2010) and Wold et al. (2011) respectively. Both concluded that early ice break-up had negative consequences for *C. glacialis* recruitment. In agreement with these previous studies, we conclude that anomalous sea ice break-up events, early or late, lead to mismatch between zooplankton and phytoplankton, resulting in low recruitment of *C. glacialis*.

Similar to *C. glacialis*, the herbivorous copepod *Pseudocalanus* spp. use ice algae for growth and development and may have been affected by the late ice algae production. Furthermore, warmer temperatures in late spring and winter seem to have enhanced the early development of *Pseudocalanus* spp., as important number of young stages were observed from December 2012 to March 2013 at the Beaufort Sea shelf break.

C. hyperboreus usually overwinters in the warm Atlantic layer and migrate upward when conditions improve the following spring. A combination of warmer water temperatures observed between 50 and 200 m and higher abundance of diatoms during the late fall and winter 2012-2013 disrupted the phenology of *C. hyperboreus*. Spring-like conditions during winter in the usually cold Pacific halocline layer led to the early awakening from diapause and upward migration of *C. hyperboreus*, resulting in increased abundance in sediment traps from January to March 2013 (Figure 2). *C. hyperboreus* is a capital breeder, i.e. using internal energy to reproduce, and studies have shown that the presence of food increase the respiration rate and fecundity of *C. hyperboreus* AF before spring bloom (Conover, 1967; Takahashi et al., 2002). Results from these studies suggest that the presence of food triggered the early awakening from diapause and increased female fecundity, leading to early reproduction and early presence of nauplii in upper waters. In addition, experiments showed that warmer water temperatures led to faster egg development and earlier hatching in Disko Bay, resulting in early nauplii appearance in both cases (Jung - Madsen et al., 2013). A faster embryonic development of *C. hyperboreus* and *C. glacialis* (Corkett et al., 1986), higher egg production for *C. glacialis* (Kjellerup et al., 2012), and a faster nauplii development were also observed under warmer temperatures (Daase et al., 2011). The unusually early presence of nauplii in sediment traps at the Beaufort Sea shelf break in March 2013 is supported by these results.

Similar to *C. hyperboreus*, peaks in nauplii abundance were correlated to the export of pelagic phytoplankton cells for most years sampled, but the early reproduction in winter 2013 disrupted this timing by creating a 13 to 15-week lag between phytoplankton export and peak in nauplii abundance, leading to an important mismatch and starvation period impacting recruitment of the new generation. Daase et al. (2011) and Ringuette et al. (2002) suggested that increased starvation time enhance mortality and that only nauplii coinciding in time with the phytoplankton bloom have the potential to recruit.

The mismatch event observed in 2013 likely had negative consequences for herbivorous copepod recruitment and for the upper food chain, as herbivorous copepods play a critical role in energy transfer in the Arctic Ocean. *C. hyperboreus* and *C. glacialis* constitute an important food source for adult polar cod (*Boreogadus saida*) (Benoit et al., 2010), the most abundant fish in the Arctic seas. Lower biomass of *Calanus* copepods resulting from this mismatch event may therefore have negative consequence on polar cod biomass. Also, the warm temperature combined with the presence of food in late fall and winter 2012-2013 generated an earlier production of nauplii and hence removed the usual nauplii production of June, the most abundant prey of polar cod larvae (Michaud et al., 1996). This mismatch may have contributed to the decline in polar cod larvae biomass observed in August 2013 in the Beaufort Sea (Geoffroy, 2016).

With the ongoing decrease in sea ice extent and increase in water temperature, such observations provide insight of the potential impact of climate change on the Arctic Ocean ecosystem. In this context, mismatches between phytoplankton and zooplankton are expected to become more frequent over the seasonally ice-covered Arctic Ocean, which would have drastic consequences for the whole Arctic food web.

This assessment of major changes occurring in the Beaufort Sea would not have been possible with the usual sampling methods such as remote sensing or field sampling, limited to ice-free periods in summer. It is therefore crucial to maintain long-term observations in the Arctic Ocean to fully understand the large range of effects induced by climate change.

In Baffin Bay, long-term measurements of the denser waters of Smith Sound will allow us to characterize the variability of hydrographic properties and velocity of the bottom waters, and to confirm or infirm that the most probable source of dense waters are those formed in winter during polynya events on the shallow Greenland shelves. Such information, along with the biogeochemical data obtained during the LTOO project, will contribute to models and other ArcticNet projects.

CONCLUSION

The identification of phytoplankton cells and zooplankton collected into sediment trap samples as part of the last phase of ArcticNet has proven to be an essential addition to the LTOO project. These continuous results improved our understanding of the impact of climate warming on marine ecosystems through the monitoring of the timing, magnitude, and composition of the phytoplankton blooms and the timing of the upward and downward migrations of herbivorous copepods. These long-term measurements performed in the Beaufort Sea, and in the Chukchi Sea and Queen Maud Gulf in collaborations with other projects, will unquestionably provide insights in changes to expect under the current warming conditions. Still, the lasting impact of climate change in the Arctic will take a few decades to fully emerge. It is therefore crucial to maintain the oceanic observatories to build the long-term dataset needed to answer the ecosystem-level questions raised by climate change.

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INTEGRATED MARINE GEOSCIENCE TO GUIDE ENVIRONMENTAL IMPACT ASSESSMENT AND SUSTAINABLE DEVELOPMENT IN FROBISHER BAY, NUNAVUT

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ABSTRACT

This project carries out integrated geological and biological seabed mapping in Frobisher Bay to help guide potential resource and infrastructure development in the region. Biological seabed mapping will identify habitat types, and determine their distribution throughout the bay by using multibeam sonar mapping. Repeated biological sampling of sites studied in the 1970s will allow us to measure ecological change in bottom flora and fauna over decadal timescales, to help measure the potential impacts of climate change on shallow marine ecosystems in the Canadian Arctic. Geological seabed mapping will identify bottom types, which support different habitat types, and will characterize the stability of the seabed. Additional marine geological studies will identify the distribution of marine geohazards, especially underwater landslides, in Frobisher Bay. Sampling of past underwater landslides identified from the sonar data will determine the timing of these events, and the likelihood of such hazards occurring in the near future. Knowing the distribution and past frequency of landslides and other hazards will help guide development decisions, such as the placement of planned infrastructure like fibre-optic cables or the proposed Port of Iqaluit.

KEY MESSAGES

- Seabed mapping in Frobisher Bay is essential for geohazard assessment and benthic community mapping.
- Inner Frobisher Bay has an unusually high abundance of submarine landslides.
- Understanding the nature and recurrence interval of marine geohazards in Frobisher Bay is essential to guiding proposed economic development activities in the bay.
- Offshore extensions of terrestrial Quaternary glacial deposits such as moraines and eskers were identified and mapped; moraines and eskers can form important hard-bottom habitats.
- Multiple seabed habitats were identified, characterized and mapped using bottom sampling and drop video transects.
- Identification and mapping of vulnerable habitat-forming benthic biota such as sponges, cold-water corals and bryozoan beds are essential to guiding sustainable fisheries development.
- A new team of marine habitat mapping researchers, including northern residents, were exposed to Arctic research.

OBJECTIVES

The objectives of this project are to:

- Map the seabed in Frobisher Bay for geohazard assessment, geomorphology and benthic biota.
- Characterize marine geohazards in Frobisher Bay, especially submarine landslides, including their nature, spatial distribution and temporal recurrence interval.
- Identify and map vulnerable marine ecosystems (VME's) in Frobisher Bay that need to be protected from fisheries or infrastructure development activities.
- Resample long-term ecological monitoring sites in inner Frobisher Bay sampled in the 1960s and 1970s, to examine long-term trends in biodiversity associated with climate change and/or onshore development.

Specific objectives for 2016 were to:

- Significantly increase multibeam sonar bathymetry coverage in areas of water depths less than 300 m in outer Frobisher Bay, especially in large areas of the bay expected to contain moraines and other offshore extensions of previously mapped terrestrial glacial features.

- Acquire deep-water multibeam sonar bathymetry coverage in areas of water depths greater than 300 m in outer Frobisher Bay.
- Collect and analyze piston cores and gravity cores with which to characterize the nature and age of submarine slope failures within inner Frobisher Bay.
- Complete the first year of resampling of long-term ecology study sites in inner Frobisher Bay.
- Deploy box cores to initiate ground-truthing of bottom types identified from multibeam sonar imagery in inner and outer Frobisher Bay.
- Describe carbonate bioclasts present within Frobisher Bay sediments.

KNOWLEDGE MOBILIZATION

Knowledge Mobilization achieved in 2016-17 included bringing teaching materials to Nunavut Arctic College, and engaging NAC students in field work. The GSC community consultation trip included presentations about the Frobisher Bay project in Iqaluit. In addition, results of project activites were presented at the ArcticNet ASM, and at the 6th International Symposium on Deep-Sea Corals.

Knowledge mobilization activities planned for 2017-18 include Iqaluit school and community centre visits to share Frobisher Bay bottom videos and bottom habitat photos with city residents. Additionally, copies of bottom videos and habitat photos, preserved specimens of marine invertebrates for teaching purchases, and summary results of various investigations, will be archived at Nunavut Arctic College, Iqaluit campus, for use in their Environmental Technologist Program. Project results will also be presented at the GEOHAB conference on Marine Geological and Biological Habitat Mapping in Halifax, in May 2017, and possibly at the International Marine Biodiversity Forum in Montreal in April 2018.

INTRODUCTION

Coastal regions of the Canadian Arctic face increasing pressures from climate change, resource exploitation, and infrastructure development (Archambault et al., 2016). These pressures come together in a crucial region of the Eastern Arctic in Frobisher Bay. Adjacent to the rapidly growing City of Iqaluit, the bay faces potential impacts from expanding commercial and subsistence fisheries, expanded terrestrial mining, increasing marine traffic, and infrastructure development for both the city and the proposed new port at Iqaluit.

As a large macrotidal embayment, Frobisher Bay presents interesting new opportunities and challenges, including the possibility of in-stream hydroelectric power generation, and localized rapid sediment transport and coastal erosion associated with sea-level rise in a macrotidal setting. Infrastructure requirements for the City of Iqaluit, for the Government of Nunavut, and for expanding the facilities of the Port of Iqaluit place additional possible stressors on Frobisher Bay, from eutrophication, sedimentation, potential oil spills, and potential introduction of marine invasive species through ballast water discharges. Natural seabed geohazards in the bay may affect infrastructure development, which in turn has the potential to trigger submarine slope failures and sediment mass transport events (Hatcher and Forbes, 2015).These stressors may interact with the seabed habitats of the bay both geologically and ecologically.

Combined bathymetric, geological and ecological seabed mapping provides a means to understand and manage these potential impacts, including potential interactions between different human activities, in an integrated fashion through marine spatial planning (Baker and Harris, 2012, GEOHAB Atlas). A medium sized bay such as Frobisher Bay is large enough to encompass a wide variety of coastal and shallow marine environments and a similarly wide range of human activities and potential stressors, yet small enough to be mapped in its entirety. Furthermore, Frobisher Bay is one of the few locations in the Canadian Arctic with a long history of geological and ecological study, providing long-term datasets and study areas that can be used to look both backward and forward. Thus, Frobisher Bay presents an ideal opportunity to demonstrate the capabilities of geological and ecological seabed mapping for understanding and managing coastal environmental change in Canada's Arctic.

Seabed mapping in Frobisher Bay addresses four major scientific questions, each with a management application.

1. Biological habitat mapping. Biological habitat mapping estimates the distribution and composition of habitat types around the bay, relying on the close links between bottom geomorphology and benthic biology (Brown et al., 2011; Copeland et al. 2012; Harris, 2012). Characterizing and mapping habitats also allows us to identify sensitive habitats that might need to be protected from expanding fisheries or infrastructure development.
2. Long-term ecological study. We are re-sampling biological monitoring sites in inner Frobisher Bay that were first studied in the late 1960's and early 1970s (Wacasey et al. 1979, 1980; Cusson et al. 2007). Resampling these sites, and placing the habitats which they inhabit within their context for the bay, allows us to estimate long-term changes in benthic communities that could accompany climate change, and to distinguish long-term directional change from short-term fluctuations (e.g., Hofmann et al. 2013).
3. Marine geohazard characterization and mapping. Inner Frobisher Bay appears to have an anomalously high incidence of submarine slope failures, which are readily mapped using multibeam sonar (cf., Campbell and Bennett, 2014). Our research in Frobisher Bay maps these submarine landslides, but more importantly characterizes the slide morphology, and uses piston cores to acquire information that contributes to our understanding of the triggering mechanisms and recurrence intervals of these natural disturbance events. Understanding the size and recurrence interval of these events, along with slope stability studies, is crucial baseline information for guiding infrastructure development.
4. Seabed characterization. Seabed characterization throughout Frobisher Bay provides crucial information to guide infrastructure development decisions. Rapid sedimentation in the macrotidal setting of Frobisher Bay already pre-conditions the bay for sediment instability. Slope stability studies, penetrometer tests, and other geotechnical assessment of the seabed in inner Frobisher Bay, combined with the multibeam sonar bathymetric mapping, provide important baseline information for coastal engineering projects associated with infrastructure development.

ACTIVITIES

Dissemination of scientific results

- Inclusion of ArcticNet imagery and preliminary results from Frobisher Bay in a presentation on Arctic coral and sponge biodiversity (6^{th} International Symposium on Deep-Sea Corals, Edinger), and in oral presentations and posters at the 2016 ArcticNet ASM (Edinger et al., Zammit).
- Description of long-term ecology initial results at the 2016 ArcticNet ASM (Aitken et al., Herder et al.).
- Public presentation in Iqaluit on March 20, 2016 by Campbell titled "Mapping the Bottom of Frobisher Bay".
- Hosted seven Nunavut MLAs for visit to MV *Nuliajuk* on October 22, 2016 to discuss seabed mapping activities.

HQP training

- Ongoing training of two MSc students (Erin Herder (MUN), Laura Broom (Dalhousie)).
- Ongoing training of two PhD students (Robert Deering (MUN), Benjamin Misiuk (MUN)).
- Nunavut Arctic College student Janice Saimaiyuk was involved in 2016 field sampling as part of the Environmental Technologist training program.
- One undergraduate honours student carried out field research (Kendra Zammit (MUN)).
- One undergraduate research assistant contributed to the analysis of the historical data set for marine benthos (Jordon Rozon (Saskatchewan)).

Field work in the Canadian Arctic in 2016

- Joint ArcticNet/CNGO/GSC cruise legs on the Nunavut Government fisheries research vessel MV *Nuliajuk*, multibeam sonar benthymetric mapping, ground-truth sampling, gravity coring. Approximately 500 km^2 were mapped in Frobisher Bay aboard MV *Nuliajuk*. Extensive ground-truth sampling in inner Frobisher Bay, and limited ground-truth sampling in outer Frobisher Bay. Approximately 30 gravity cores collected.
- Box-cores, Agassiz trawls, six piston cores and deep-water multibeam sonar bathymetric mapping in outer Frobisher Bay aboard CCGS *Amundsen*.
- Carbonate bioclasts from inner Frobisher bay were collected for ongoing studies on cold-water carbonate sediments in the Canadian Arctic.

Laboratory work, instrumentation, analysis

- Post-cruise processing of multibeam sonar data ongoing at MUN and MUN Marine Institute.
- Video transects from 2016 expedition under analysis at MUN (see Results).
- Benthic samples from 2016 expedition under analysis at MUN (see Results).
- Analysis of 2016 piston cores has been completed at the Bedford Institute of Oceanography. Observations and measurements included visual core description, split core x-radiography (see Results) and photography, shear strength, gamma density, p-wave velocity, electrical resistivity, magnetic susceptibility and colour spectrophotometry. Subsamples were collected for grain size analysis, clast lithology and radiocarbon dating.
- Constituent analysis of carbonate bioclasts samples including weights by higher taxon and by species has been completed at MUN.

Other activities

- Extensive networking with ArcticNet Hidden Biodiversity project.
- Networking with European researchers studying cold-water carbonate sediment producers the Eurasian Arctic through COCARDE network (Cold-water carbonates in Shallow and Deep Time).
- Collaboration with activities of the Geological Survey of Canada (Natural Resources Canada), in particular related to the Public Safety Geoscience Program (surficial geology, seabed hazards including seismicity, faulting, and seeps) and the Climate Change Geoscience Program (sea-level change, sea ice, and wave climate, erosion and sediment transport, harbour shoaling, and other issues pertinent to urban and port development in Iqaluit). Work related to port development also addresses Transport Canada priorities.
- Educational materials, including curated samples and underwater video clips, based on biota and habitats observed in Frobisher Bay, are under preparation for the Nunavut Arctic College Environmental Technology program.

RESULTS

Bathymetric Mapping aboard MV Nuliajuk and CCGS Amundsen

Approximately 500 km^2 of the seabed were mapped in Frobisher Bay during the MV *Nuliajuk* combined Legs 1, 2, and 5 (Figure 1).

Two areas of outer Frobisher Bay were mapped by CCGS *Amundsen* during the 2016 mission: a deep-water polygon in northwestern outer Frobisher Bay (see polygon A in Figure 2; approximately 100 km^2), and an along-track swatch along the southeastern edge of outer Frobisher Bay (see polygon B in Figure 2).

Field sampling aboard CCGS Amundsen (E. Herder, E. Edinger) and MV Nuliajuk (A. Aitken, E. Herder, B. Misiuk, T. Tremblay, J. Fraser, K. Zammit)

Field sampling aboard CCGS *Amundsen* and MV *Nuliajuk* had two purposes: to ground-truth multibeam sonar backscatter data both geologically and biologically, and to re-sample long-term ecology sites near Iqaluit in inner Frobisher Bay.

Summary of research activities

- CCGS *Amundsen* (July 14-28, 2016) – Benthic box core samples collected at two long-term ecology sites (triplicate samples) in inner Frobisher Bay near Cairn Island on July 16, 2016.
- CCGS *Amundsen* (July 14-28, 2016) – Benthic box core samples collected at 6 slope failure sites and 1 "off" slope failure site near Hill Island on July 15 and 16, 2016.
- CCGS *Amundsen* (July 14-28, 2016) – One Agassiz trawl collected in inner Frobisher Bay (FB4 – July 16, 2016), one Agassiz trawl collected in outer Frobisher Bay (FB7 – July 17, 2016).
- MV *Nulialjuk* (October 9-15, 2016) – Benthic grab samples and towed video samples collected in inner Frobisher Bay near Iqaluit, Cairn Island, and Hill Island.

Nineteen box cores were collected from Frobisher Bay in 2.5 days of CCGS *Amundsen* field work within the bay: fourteen in the inner bay (Figure 3), and five in the outer bay (Figure 4), including triplicate sampling at one deep water outer bay site. Frobisher Bay box cores were processed following standard protocols aboard CCGS *Amundsen*, with the exception that they were subsampled for microbiota (i.e., Casey Hubert research project) and for thyasirid bivalves (i.e., Rachelle Dove, Hidden Biodiversity project). The primary emphasis was on repeat sampling of long-term ecology sites in iner Frobisher Bay that were first sampled in the 1960s and 1970s, with a secondary emphasis on broader habitat mapping, especially in deep-water portions of the bay beyond the operational capacbility of MV *Nuliajuk*. Only two Agassiz trawl samples (Stations FB4 and FB7-1) were collected (see Figures 3 and 4), due to fear of damaging the trawl on hard bottoms. Agassiz trawl processing was also limited by the shortage of personnel: the leader of the benthic team for the *Amundsen* cruise Leg 2a (Alec Aitken) had to withdraw for medical reasons immediately before the start of the cruise leg.

Sampling aboard MV *Nuliajuk* employed a Van Veen or petite Ponar grab sampler to collect seabed sediments and biota, and the Deep Blue SplashCam underwater drop video camera for bottom video transects to acquire information related to seabed topography, geology and biota. The benthic habitat mapping portion of the 2016 MV *Nuliajuk* field work resulted in the acquisition of a data set of underwater video, as well as seabed sediment and biological samples, across a broad area of the seabed (Figures 5 and 6). Out of 301 attempted grab samples 235 yielded sediments, biota, or both. A total of 91 four-minute underwater video drifts were recorded, yielding over six hours of continuous video data for analysis. The habitat mapping sampling effort exceeded expectation, and will provide critical insight into the distribution of benthic biota in Frobisher Bay.

The contents of each grab sample were photographed. From the grab samples recovered, two duplicate 125 ml subsamples of sediment were collected and frozen for later analysis (particle size distribution, organic matter content) before the remaining sediment was sieved through a 1 mm mesh screen. All flora and fauna retained on the screen were fixed in 10% formalin in seawater, before being transferred to 70% ethanol in seawater. Grab samples in some areas in the northwest of Frobisher Bay, near Iqaluit, yielded sediments with significant amounts of dark, anoxic, organic matter. Grab samples further south consisted largely of muddy sediments, with with variable proportions of gravel and cobbles. Sediment samples in the southeast, near the "mid-bay islands" area consist largely of gravel.

All 12 long-term ecology sites were successfully sampled during Leg 3d. This included 12 four-minute camera drifts and 50 grab attempts, of which 38 were successful at collecting a sediment sample, a biological sample, or both (in most cases) resulting in triplicate samples for each site (Figure 6). Forty-seven underwater video transects (each of 4 minutes duration) and 175 grab samples were attempted at slope-failure and habitat mapping sites (Figure 6), of which 139 attempts were successful in returning either a sediment sample only, a biological sample, or both.

Underwater video yielded data on benthic biota and seabed substrates. Expansive areas of fine-grained, muddy substrate were visible in much of the west and south Frobisher Bay (Figure 7) from underwater video. The southeastern, "mid-bay islands" portion of Frobisher Bay was dominated by rocky and boulder substrates, sometimes covered by a thin mud veneer (Figure 8). Muddy sediments, such as those seen in the northwest and west parts of the bay often exhibited a high abundance of ophiuroid echinoderms (brittlestars) and polychaete worm tubes (see Figure 9h). Rocky, high-relief substrates in the southeast part of the bay exhibited a more diverse epifauna, with significant numbers of ophiuroid echinoderms,

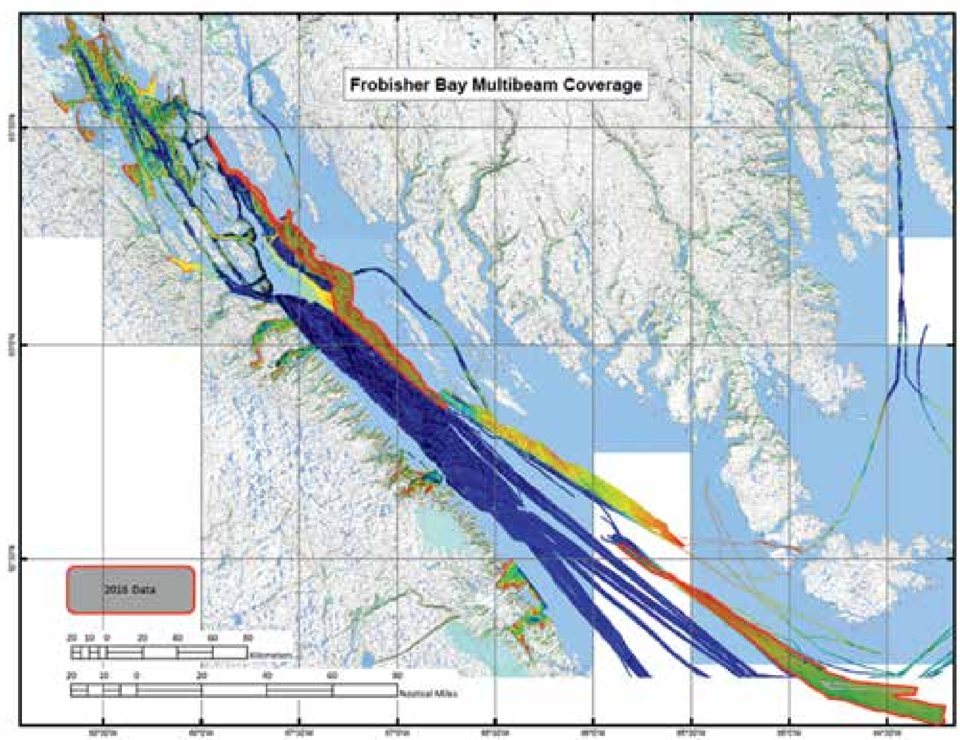


Figure 1. Map showing areas surveyed using multibeam sonar aboard MV Nuliajuk in 2016, outlined in red.

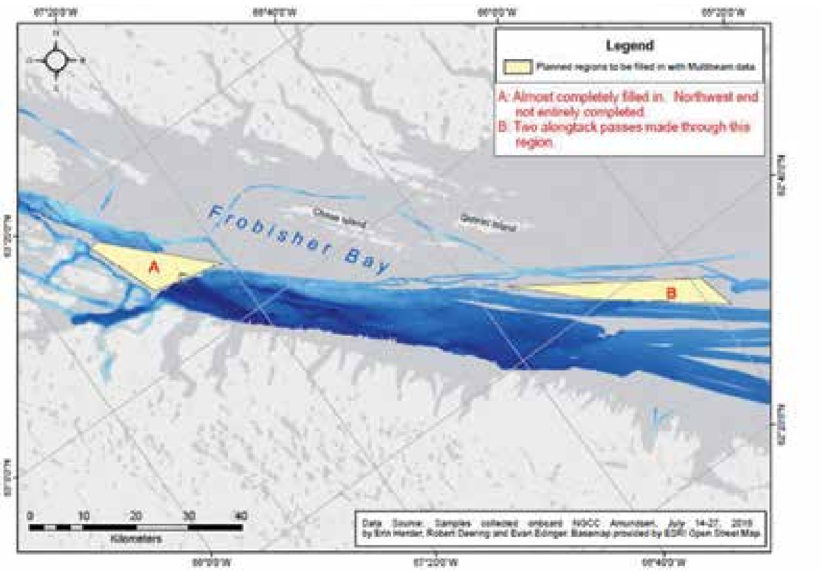


Figure 2. Map showing areas surveyed using multibeam sonar aboard CCGS Amundsen, July 14-27, 2016.

crinoids, gastropods, bivalves, pycnogonids (sea spiders), and ascidians. This shift in substrate texture, and the associated fauna, was abrupt and significant; analysis on the distribution of benthic habitats will provide insight into the drivers of these very different benthic habitats.

Benthic community structure and habitat mapping in Frobisher Bay: long-term ecology in an Arctic coastal bay (E. Herder, B. Misiuk, A. Aitken, E. Edinger)

This project will assess the nature of long-term change within benthic marine communities sampled between 1967-1976 in inner Frobisher Bay, a macrotidal estuary in southern Baffin Island (Wacasey et al. 1979, 1980) and 2015-2017. The objective of this research is to characterize benthic community change on both small and large spatial (meters to kilometers) and temporal (inter-annual vs. inter-decadal) scales in inner Frobisher Bay. This will be accomplished by comparing historical data related to benthic community structure (i.e., species composition and abundance, 1967-1976) acquired from grab samples with benthic fauna collected at the same sites between 2015 and 2017. Additionally, the benthic community at a naturally disturbed slope failure site near Hill Island in inner Frobisher Bay will be compared with the benthic community sampled at sites not affected by this slope failure to investigate the effects of known natural disturbance on the benthos. In this report we will focus our attention on two stations, Station 5 (63°40'23.02" N, 68° 25' 44.05" W) and Station 5b (63°43'32.1" N, 68° 31' 18.59" W), that have been sampled repeatedly across both time periods, providing rich data sets that will facilitate spatial and temporal comparisons of benthic community structure.

In July 2016, two long-term ecology sites (triplicate samples) and six slope-failure sites (single samples) were successfully collected using a box core onboard the CCGS *Amundsen*. In October 2016, an additional forty-seven stations were sampled using an underwater towed video system and 45 stations were sampled (triplicate samples) using a Van Veen and Petite Ponar grab sampler onboard the MV *Nulialjuk*. Preliminary analysis has begun for benthic samples collected at two long-term ecology stations, Station 5 and Station 5b. The results of the analysis of the towed video and grab samples for these stations are presented here.

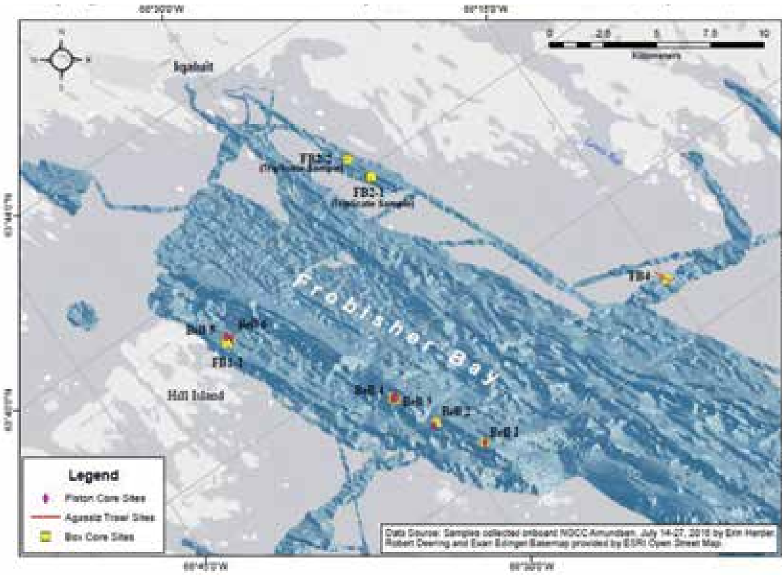


Figure 3. Map of sampling locations in inner Frobisher Bay sampled onboard CCGS Amundsen, July 14-27, 2016.

A 4:04 minute underwater video transect was obtained at station 5b that resulted in 49 screen captures (i.e., screen capture acquired every 5 seconds). Screen captures at this station indicate that the sediment along the length of the transect is sandy silt. Dominant algae include the kelp *Laminaria* sp. (present in approximately 70% of screen captures) and *Agarum* spp. (observed in just under 50% of screen captures; Figure 9a). Other algae were present in smaller amounts including an unidentified filamentous brown alga, and an unidentified red alga. A brown bacterial mat was observed on the sediment surface in some screen captures. The soft-shelled clam, *Mya truncata* (one recorded), the crinoid echinoderm *Heliometra glacialis* (nine recorded), and an unidentified gastropod (cf. *Buccinum* sp.; four recorded) were also observed.

A 4:56 minute underwater video transect was obtained at Station 5 that resulted in 56 screen captures. The seabed at this station was uneven in places, reflecting the structure of the underyling bedrock, and was covered with fine sediment. This station was dominated by ophiuroid echinoderms (over 100 were recorded in screen captures).

Ascidians and the isopod *Arcturus* sp. were also relatively abundant at this station (Figure 9b). Less abundant organisms observed in the video images include pycnogonids (one recorded), an unidentified gastropod (cf. *Buccinum* sp.; one recorded), pieces of branching bryozoan (two recorded), a ball-like sponge (three recorded), and an unidentified yellow sponge (one recorded).

In addition to the long-term ecology sites, one towed video transect was acquired at station C-IF-27 (62° 15’ 52.43” N, 65° 06’ 7.85” W) slightly north of the Hill Island slope-failure. This transect was 4:05 minutes and resulted in 49 screen captures. This station was characterized by a silty bottom with numerous rocks (> 5 cm diameter) observed in most screen captures. Ophiuroid echinoderms dominated at this station with over 200 individuals recorded amongst the screen captures. Crinoids were also abundant throughout this site (at least 20 were recorded in screen captures). At least four species of sponges, numerous sea urchins, and a small number of gastropods and pycnogonids were also observed at this station. Rocks observed throughout the video transect had encrusting organisms on them. Bivalve shell hash was also abundant throughout the screen captures for this transect (Figure 9c).

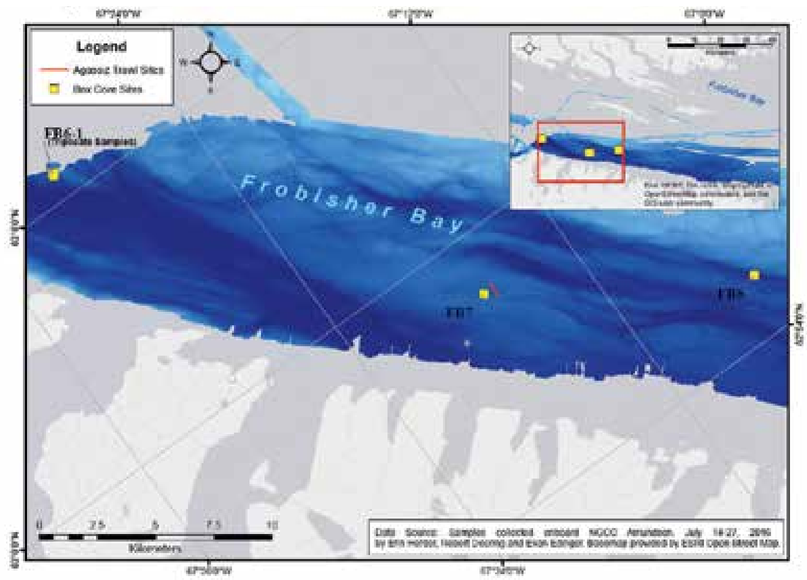


Figure 4. Map of sampling locations in outer Frobisher Bay sampled onboard CCGS Amundsen, July 14-27, 2016.

On-board observations of the benthos recovered in grab samples at long-term ecology sites near Iqaluit include the bivalve *Yoldia hyperborea* and ophiuroid echinoderms. Observations of the benthos recovered in grab samples at long-term ecology sites near Cairn Island include bryozoans and ophiuroid echinoderms (Figure 9d), the bivalves *Clinocardium ciliatum* and *Serripes groenlandicus* (Figure 9e), and many tubiculous polychaete tubes and worms. Near the Hill Island slope failure site red and brown algae, bivalves, pycnogonids (Figure 9f), ophiuroid echinoderms, tubiculous polychaetes (Figure 9g), unidentified worm tubes (Figure 9h), and the isopod *Arcturus* sp. were observed. Benthic grab samples have been sorted for long-term ecology stations 5b and 28 (63°42'35.18" N, 68°31'17.02" W). The dominant group of organisms among all replicates of benthic grab samples at station 5b was polychaete worms. One replicate accounted for over 300 worms and/or tubes. Amphipods (21 recorded in all replicates) and bivalves (16 recorded in all replicates) were present in small numbers, followed by gastropods (four recorded in all replicates) and ophiuroid echinoderms (two recorded in all replicates). One replicate sample contained a large amount of filamentous brown algae. Station 28 is located approximately 500 metres from station 5b. Amphipods were the dominant group of organisms in two of three replicate samples at this site (a total of 69 amphipods were recorded in all replicates). Polychaete worms were present in much lower abundance (a total 18 recorded in all replicates). Bivalves, isopods, ophiuroid echinoderms, and unidentified fish were all present; each group of organisms is represented by fewer than six individuals each.

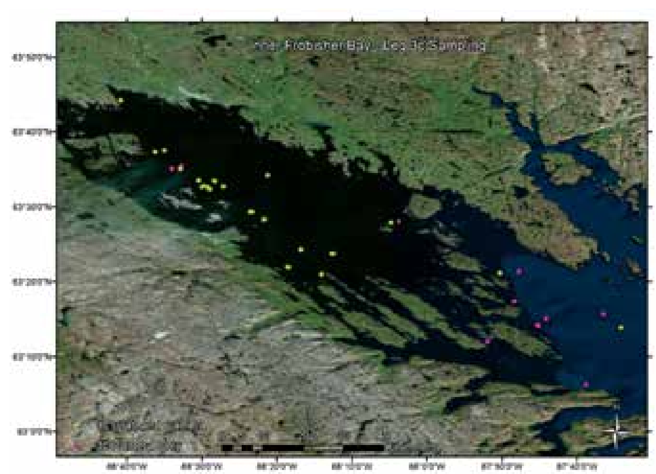


Figure 5. Map of sampling locations in inner and outer Frobisher Bay sampled onboard MV Nuliajuk, October 5-8, 2016.

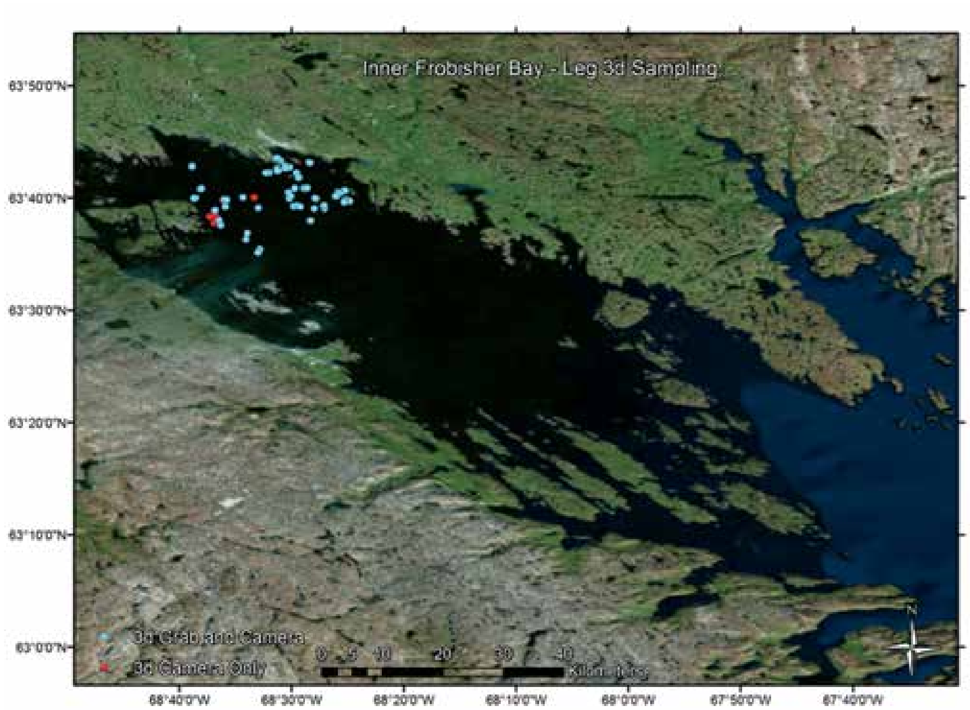


Figure 6. Map of sampling locations in inner Frobisher Bay sampled onboard MV Nuliajuk, October 9-15, 2016.

Analysis of the historical sample data collected by Wacasey et al. (1979, 1980) between 1967 and 1976 was also completed for station 5b and 5. A summary of the dominant species observed in the historical data set for these stations is summarized in Table 1. Using the statistical package R, the general linear model was employed to identify whether a significant relationship exists between the number of species collected lmPerm package, R). Station 5b indicated a statistically significant relationship between species diversity and year sampled at the α = 5% level. A decrease in number of species from 1969 to 1972 was followed by an increase in number of species in 1976 (Figure 10a). Station 5 indicated a statistically significant relationship between species diversity and year sampled at the α = 10% level. A decline in number of species from 1968 to 1969 was followed by an increase in number of species in 1970 (Figure 10b). Additionally, the general linear model was used to identify whether a relationship existed between number of species collected and sampling season ("ice cover" and "ice free" seasons) and water depth. Both variables indicated a statistically

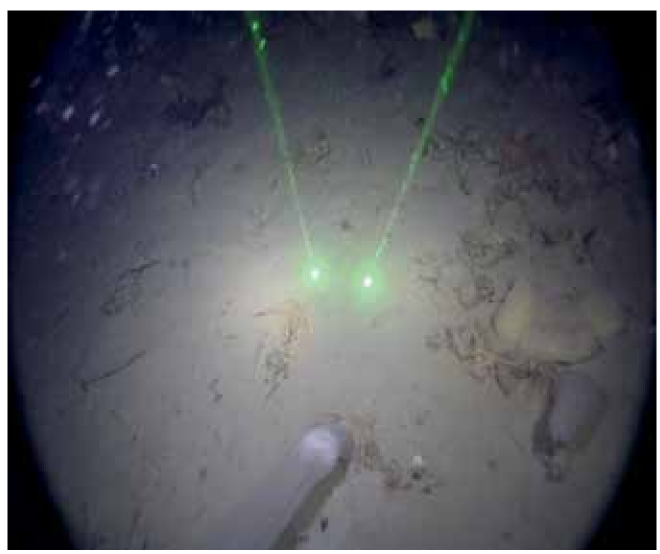


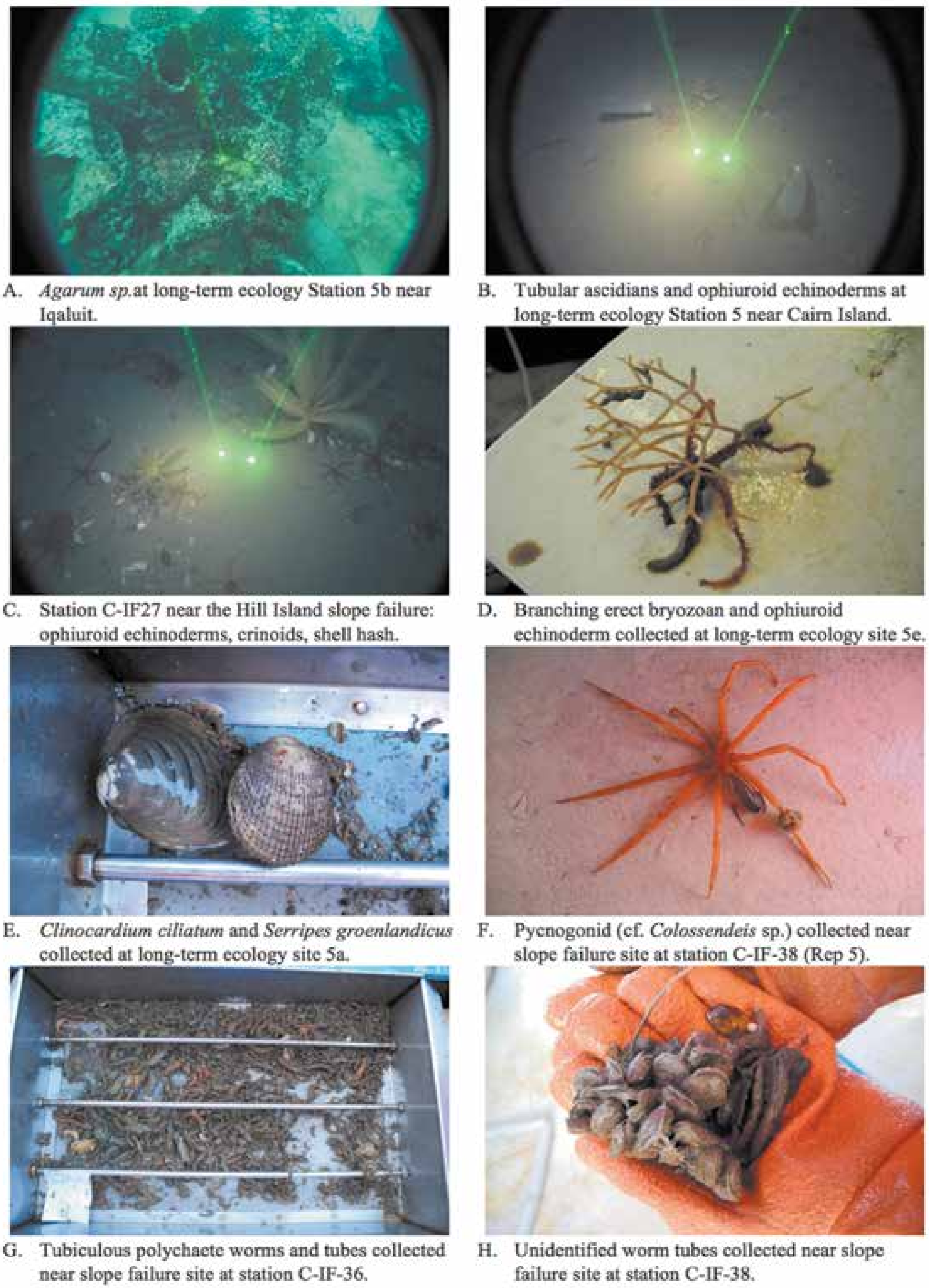
Figure 7. Muddy seabed recorded in an underwater video transect. Organisms visible in the field of view include a large tubular ascidian, several ophiuroid echinoderms and sponges.

Figure 8. Rocky seabed recorded in an underwater video transect. Organims visible in the field of view include a crinoid, a large gastropod (cf. Buccinim sp.), several pycnogonids and empty, thick-walled mud tubes constructed by polychaete worms.

significant relationship at the α = 5% level (Figure 10c, d). A greater number of species were recovered during the "ice free" season versus the "ice cover" season. Species diversity was observed to increase along a depth gradient from the intertidal zone to 80 m depth.

The historical data set presented by Wacasey et al. (1979, 1980) includes information related to the species composition, abundance and biomass of marine invertebrates and fishes collected by a bottom dredge. The dredge consisted of an iron frame, 36 inches wide, to which a 2 m length of net was attached: the mesh size of the net at the cod end was 0.5 cm. Thirteen dredge samples were recovered in the Station 5 area at depths ranging from 40-68 m in 1969, 1970, and 1973 (Table 2). All of the dredge samples were acquired in the month of August (i.e., ice free season). The number of species recovered in individual dredge samples ranges from 19 to 28, while replicate samples yielded species counts ranging from 13 (n=2) to 61 (n=4). The average dry weight biomass for all 13 dredge samples is 337.1 ± 243.3 g/m^2 (Table 2). The dominant groups of benthic organisms with respect to the proportion of total biomass recorded in the dredge samples are ascidians, ophiuroid echinoderms (brittlestars), and sponges; bivalves, polychaetes, and echinoid echinoderms (sea urchins) are also important (Table 3).

An Agassiz trawl was deployed from CCGS *Amundsen* in July, 2016 to sample the benthos in inner Frobisher Bay. The trawl collects epifaunal and shallow infaunal organisms, many of which can be observed in towed video images as noted above, thus providing ground truth to facilitate identification of the organisms observed in the screen captures. We report on the materials recovered in Agassiz trawls at Stations FB4 and FB7-1 (Table 4; see sampling locations in Figures 3 and 4). Please note that biomass is reported as wet weight expressed in grams. At Station FB4, ascidians (5904 g), barnacles (346 g), ophiuroid echinoderms (notably *Ophiocten sericeum*, 167 g), and bivalves (notably *Hiatella arctica*, 398 g; *Musculus niger*, 274 g) contribute significantly to the biomass of the benthos recovered in this 4 minute trawl. At Station FB7-1, the polychaete *Pectinaria granulata* (109 g) and the ophiuroid echinoderm *Ophiocten sericeum* (255 g) contribute the greatest proportion of the biomass recovered in this 6 minute trawl.



A. *Agarum sp.*at long-term ecology Station 5b near Iqaluit.

B. Tubular ascidians and ophiuroid echinoderms at long-term ecology Station 5 near Cairn Island.

C. Station C-IF27 near the Hill Island slope failure: ophiuroid echinoderms, crinoids, shell hash.

D. Branching erect bryozoan and ophiuroid echinoderm collected at long-term ecology site 5e.

E. *Clinocardium ciliatum* and *Serripes groenlandicus* collected at long-term ecology site 5a.

F. Pycnogonid (cf. *Colossendeis* sp.) collected near slope failure site at station C-IF-38 (Rep 5).

G. Tubiculous polychaete worms and tubes collected near slope failure site at station C-IF-36.

H. Unidentified worm tubes collected near slope failure site at station C-IF-38.

Figure 9. Marine organisms observed in towed video transects and benthic grab samples collected in October, 2016. Laser beams define a scale of 5 cm in frames A-C.

Table 1. Summary of benthic sample data collected at Stations 5b and 5 from Wacasey et al. (1979, 1980).

Station	Date	No. of Species Collected	Density (#/m^2)	Total Biomass (g/m^2)	Dominant Species by Biomass (g/m^2)		
					1st Most Dominant	2nd Most Dominant	3rd Most Dominant
5b	29-Jul-69	59	24,888	8.65	*Dipolydora quadrilobata (1.79)*	*Microspio sp. (1.33)*	*Eteone flava/longa (1.14)*
	3-Sep-69	66	12,895	16.71	*Serripes groenlandicus (4.24)*	*Astarte borealis (3.72)*	*Eteone flava/longa (1.05)*
	9-Jan-70	44	23,620	8.99	*Dipolydora quadrilobata (2.13)*	*Astarte borealis (2.08)*	*Eteone flava/longa (1.09)*
	21-May-70	43	21,503	12.78	*Eunoe oerstedi (2.82)*	*Priapulus caudatus (2.27)*	*Nephtys ciliata (1.84)*
	9-Feb-72	42	7,040	4.96	*Priapulus caudatus (2.72)*	*Unid. nemertean sp. (0.44)*	*Nephtys ciliata (0.28)*
	17-May-72	29	278.8	6.42	*Priapulus caudatus (2.67)*	*Macoma calcarea (1.34)*	*Nephtys ciliata (0.58)*
	24-Mar-73	39	2,700	1.26	*Macoma calcarea (0.35)*	*Praxillella praetermissa (0.26)*	*Paroediceros lynceus (0.08)*
	29-May-73	48	7,463	6.68	*Buccinum hydrophanum (1.96)*	*Ennucula tenuis (1.09)*	*Phyllodoce groenlandica (0.78)*
	8-Aug-73	57	6,783	6.45	*Praxillella praetermissa (2.71)*	*Heteromastus sp. (0.49)*	*Nephtys ciliata (0.36)*
	19-Aug-76	72	13,700	15.17	*Praxillella praetermissa (2.73)*	*Nephtys ciliata (1.96)*	*Macoma calcarea (1.69)*
5	23-Jul-68	139	6,6633	35.37	*Hiatella arctica (8.64)*	*Pista elongata (4.77)*	*Nephtys paradoxa (4.70)*
	20-Aug-68	135	7,683	21.75	*Balanus balanus (5.18)*	*Nicomache lumbricalis (3.70)*	*Clinocardium ciliatum (2.69)*
	3-Sep-68	124	4,123	39.59	*Golfingia (Golfingia) margaritacea (16.92)*	*Hiatella arctica (6.84)*	*Ciona intestinalis (4.65)*
	8-Oct-68	129	13,407	27.87	*Psolus fabricii (9.76)*	*Clinocardium ciliatum (3.0)*	*Ascidia callosa (2.18)*
	5-Jan-69	111	11,115	12.32	*Ciona intestinalis (4.69)*	*Nicomache lumbricalis (1.54)*	*Ophiacantha bidentata (1.21)*
	14-Mar-69	132	25,343	12.39	*Clinocardium ciliatum (2.79)*	*Musculus niger (1.26)*	*Unid. sponge sp. (1.17)*
	14-Jun-69	125	12,855	12.73	*Nicomache lumbricalis (5.18)*	*Unid. sponge sp. (1.34)*	*Balanus balanus (0.92)*
	23-May-70	138	9,210	17.31	*Clinocardium ciliatum (4.86)*	*Nicomache lumbricalis (1.79)*	*Unid. nemertean sp. (1.39)*
	6-Aug-70	159	7,703	25.82	*Nicomache lumbricalis (5.87)*	*Hiatella arctica (3.85)*	*Polymastia sp. (2.37)*

Given our interest in documenting long-term change in the benthos in inner Frobisher Bay, it is worth noting that a variety of invertebrate species collected by a benthic dredge between 1969 and 1973 in the Station 5 area were also collected by an Agassiz trawl at Station FB4 in 2016 (Table 5). These organisms include amphipods, isopods, shrimps, echinoderms, bivalves, gastropods, and sponges. Amongst these organisms, *Balanus* sp., *Psolus* sp., *Ophiocantha bidentata*, *Clinocardium ciliatum*, *Hiatella arctica*, and *Polymastia* sp. are commonly associated with the greatest proportions of the biomass of the benthos (cf. Table 1).

Seabed Mapping, Piston Coring and Gravity Coring (R. Deering, T. Bell, C. Campbell, L. Broom, D. Forbes)

For 2016-2017, much of our effort was directed towards compiling the available geophysical data in the study area (Mate et al., 2015). Within Frobisher Bay, the acoustic stratigraphy was digitally mapped over much of the bay. Moraines and eskers observed on the seabed in inner Frobisher Bay represent offshore continuations of similar features previously mapped on land. It is not uncommon to find submerged moraines and other glacial features in fjords, where they create distinct habitat types (e.g., Dale et al., 1989; Copeland et al. 2012). The stony substrates associated with moraine surfaces (e.g., Station FB7) support a distinctive biological assemblage from muddier-bottom sites as noted above.

Sampling of submarine slope failures in inner Frobisher Bay occurred in July and September of 2016, aboard the CCGS *Amundsen* and MV *Nuliajuk*, respectively. Aboard CCGS *Amundsen*, a 10 m piston corer was used to capture an intact stratigraphy record from six sites, both disturbed and undisturbed (Figure 3). These cores are all approximately 5 m in length. Taken in conjunction with these piston cores were push cores recovered from box cores to capture the near-seabed sediments. Aboard MV *Nuliajuk* a 2.6 m gravity corer was used to collect sediments from submarine slope failure footprints in a variety of settings in the inner bay (Figures 11 and 12). The gravity corer was deployed 32 times and more than 18 m of core was recovered. All samples are currently archived at the Bedford Institute of Oceanography.

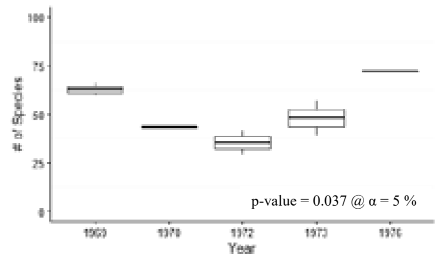
Table 2. Associated data for benthic dredge samples and the biomass of benthic invertebrates recovered from dredges collected from the Station 5 area, 1969-1973 (after Wacasey et al., 1979).

Dredge Number	Date	Water Depth (m)	Number of Dredges	Sampled Area (m^2)	Dry Weight Biomass (g/m^2)	Number of Species
D-2	Aug. 27, 1969	64-66	5	372	271.3	33
D-3	Aug. 27, 1969	53	4	264	1050.2	61
D-20	Aug. 2, 1970	68	2	93	330.1	13
D-21	Aug. 2, 1970	68	1	46	246.3	19
D-22	Aug. 2, 1970	60	2	109	59.3	21
D-23	Aug. 4, 1970	55-58	2	114	247.6	29
D-24	Aug. 4, 1970	58	2	148	75.9	25
D-6	Aug. 9, 1973	48	2	138	181.9	32
D-7	Aug. 9, 1973	40	2	151	440.5	41
D-8	Aug. 11, 1973	50	1	68	234.4	28
D-9	Aug. 14, 1973	55	2	118	536.4	25
D-10	Aug. 14, 1973	60	2	138	423.0	27
D-11	Aug. 14, 1973	54	1	65	285.3	23
				Mean S.D.	337.1 ± 243.3	

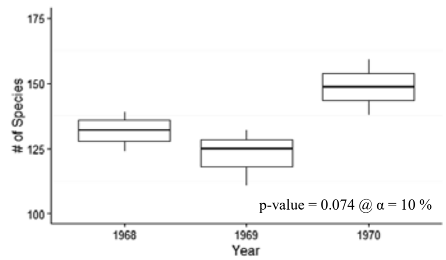
Table 3. The dominant taxa contributing to the biomass of the benthos recovered from dredges collected from the Station 5 area, 1969-1973 (after Wacasey et al., 1979).

Dredge Number	Date	Dry Weight Biomass (g/m^2)	1st Most Dominant Taxon	2nd Most Dominant Taxon	3rd Most Dominant Taxon
D-2	Aug. 27, 1969	271.3	Sponges (146.1 g/m^2)	Ophiuroids (66.5 g/m^2)	Ascidians (24.2 g/m^2)
D-3	Aug. 27, 1969	1050.2	Ascidians (494.0 g/m^2)	Ophiuroids (395.5 g/m^2)	Sponges (99.5 g/m^2)
D-20	Aug. 2, 1970	330.1	Sponges (283.2 g/m^2)	Ophiuroids (13.7 g/m^2)	Ascidians (12.0 g/m^2)
D-21	Aug. 2, 1970	246.3	Sponges (151.3 g/m^2)	Ascidians (48.2 g/m^2)	Ophiuroids (21.2 g/m^2)
D-22	Aug. 2, 1970	59.3	Ophiuroids (31.7 g/m^2)	Ascidians (11.4 g/m^2)	Polychaetes (4.6 g/m^2)
D-23	Aug. 4, 1970	247.6	Ascidians (144.0 g/m^2)	Bivalves (48.5 g/m^2)	Ophiuroids (19.2 g/m^2)
D-24	Aug. 4, 1970	75.9	Ascidians (31.3 g/m^2)	Ophiuroids (27.9 g/m^2)	Polychaetes (6.1 g/m^2)
D-6	Aug. 9, 1973	181.9	Ascidians (120.7 g/m^2)	Ophiuroids (28.6 g/m^2)	Bivalves (12.9 g/m^2)
D-7	Aug. 9, 1973	440.5	Ophiuroids (140.4 g/m^2)	Sponges (85.1 g/m^2)	Ascidians (49.7 g/m^2)
D-8	Aug. 11, 1973	234.4	Ascidians (148.7 g/m^2)	Ophiuroids (49.7 g/m^2)	Sponges (16.2 g/m^2)
D-9	Aug. 14, 1973	536.4	Ascidians (222.2 g/m^2)	Sea Urchins (117.7 g/m^2)	Sponges (74.5 g/m^2)
D-10	Aug. 14, 1973	423.0	Sponges (252.5 g/m^2)	Ophiuroids (103.8 g/m^2)	Ascidians (18.0 g/m^2)
D-11	Aug. 14, 1973	285.8	Sponges (131.8 g/m^2)	Ophiuroids (59.6 g/m^2)	Ascidians (49.9 g/m^2)

In January 2017, all of the core samples were split, analyzed, and described. Preliminary results show a change in the character of the inner bay during the past seven thousand years, possibly setting up conditions for submarine slope failure in the basin. Shell samples have been collected from all piston cores for dating control of the changes in character, as well as for bracketing the ages of the slope failures sampled (Figure 13).



A. Significant change in the number of species collected over 5 years at Station 5b.



B. Significant change in the number of species collected over 3 years at Station 5.

Figure 10. Boxplots presenting trends in the historical data for the number of species plotted against the variables: year, season, and water depth.

The *Nuliajuk* gravity cores show the variety of settings in which submarine slope failures have occurred in inner Frobisher Bay. Analysis has shown that some penetrated deep enough to collect disturbed sediment (Figure 14), while others just profile the overlying post-failure sedimentation. Those cores that penetrated slope failures will be used to date the slope failures, where suitable datable materials were collected. All of the *Nuliajuk* cores will be used to better understand the different sedimentary contexts present in the inner bay.

In Pond Inlet, a preliminary surficial geology map was developed that provides the depositional context for the Holocene paleoseismicity/ depositional history of a large basin in the inlet. Sediment core data consisting of core descriptions, photographs, x-radiographs, and physical properties were compiled for the five piston cores that will make up the Pond Inlet study. A core from Frobisher Bay that was collected in 2016 for comparison to Pond Inlet

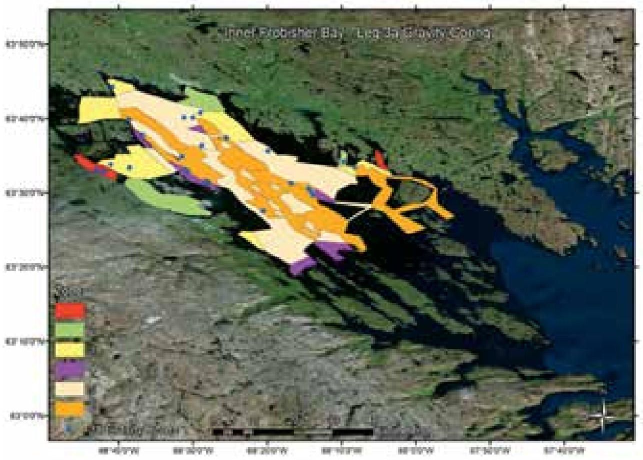


Figure 11. Deployment of the piston corer aboard CCGS Amundsen.

Figure 12. Gravity cores collected onboard MV Nuliajuk.

Figure 13. X-radiograph showing the shell sampled at the interface between disturbed and post-failure sediments.

was processed at the Geological Survey of Canada-Atlantic core facility.

DISCUSSION

Ongoing field work in Frobisher Bay continues to increase the area of multibeam coverage, but especially to unlock the marine geological and biological history of the region. Our approach of multibeam sonar mapping combined with targeted sampling using piston cores, gravity cores, box cores, and underwater video is illuminating the nature of submarine slope failures and other geological hazards within the bay. Radiocarbon dating of bioclasts found within the piston cores will help determine the age of the most frequent slope failure activity. While it is possible that enough slope failures have now been cored to help determine a chronology and recurrence interval, we will have to wait for radiocarbon results to make these interpretations.

Our analysis of historical datasets will set the context for distinguishing short-term seasonal and interannual fluctuation in biological assemblages from long-term (decadal) changes potentially associated with climate change. In particular, by placing these assemblages within their spatial context, and understanding the spatial and bathymetric variation in bottom types and biological habitats, we will be able to go far beyond a baseline dataset against which to measure future changes.

CONCLUSION

2016-17 was the most intensive year of field work for the Frobisher Bay integrated marine geoscience project, with intensive sampling from the CCGS *Amundsen*

Table 4. Associated data for Agassiz trawl samples recovered from Stations FB4 and FB7-1 occupied on Leg 2a, July, 2016 aboard the CCGS Amundsen.

Station	Date		Latitude (North)	Longitude (West)	Water Depth (m)	Duration (minutes)
FB4	July 16, 2016	Start	63° 33.340	68° 14.846	104	3
		Finish	63° 33.855	68° 15.306	75	
FB7-1	July 17, 2016	Start	62° 58.792	67° 16.367	443	6
		Finish	62° 58.398	67° 16.406	443	

Table 5. A comparison of the benthic invertebrate species collected by a benthic dredge between 1969 and 1973 from the Station 5 area, and by an Agassiz trawl at Station FB4 in 2016.

Species	1969	1970	1973	2016
Stegocephalus sp.		X		X
Balanus sp.	X	X	X	X
Argis dentata			X	X
Lebbeus sp.		X		X
Sclerocragnon sp.	X	X	X	X
Spirontocaris sp.	X	X	X	X
Arcturus sp.		X	X	X
Heliometra glacialis	X	X	X	X
Strongylocentrotus droebachiensis		X	X	X
Psolus sp.		X	X	X
Ophiocantha bidentata	X	X	X	X
Ophiocten sericeum	X	X		X
Boreotrophon sp.	X	X	X	X
Colus islandicus			X	X
Margarites groenlandicus	X		X	X
Margarites umbilicalis			X	X
Natica clausa			X	X
Neptunea sp.	X		X	X
Velutina sp.	X	X	X	X
Clinocardium ciliatum	X	X	X	X
Musculus discors	X	X	X	X
Musculus niger	X	X	X	X
Nuculana pernula	X	X	X	X
Pandora glacialis	X	X		X
Polymastia sp.	X		X	X
Hiatella arctica	X	X	X	X

over several days, combined with extensive mapping and sampling over several weeks on the MV *Nuliajuk*. All datasets collected are presently under analysis. Project student recruitment goals were mostly met, including the goal of involving northern students in field sampling in Frobisher Bay as part of the Nunavut Arctic College Environmental Technology Program.

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INNOVATIVE RESEARCH ON MONITORING MARINE MAMMALS TO MITIGATE IMPACTS OF A CHANGING ARCTIC

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Brent Young (University of Manitoba)

HQP

Cassandra Debets, Doctoral Student (University of Manitoba)
Sarah Fortune, Doctoral Student (University of British Columbia)
Evaluating the energetic consequences of environmental change for bowhead whales in the Eastern Canadian Arctic
Melissa Galicia, Doctoral Student (York University)
Stephen Hamilton, Doctoral Student (University of Alberta)
Anthropogenic effects of humans on polar bears in the Beaufort Sea
Amy Johnson, Doctoral Student (University of Alberta)
Jody Reimer, Doctoral Student (University of Alberta)
Luana Sciullo, Doctoral Student (York University)
Kristin Westdal, Doctoral Student (Fisheries and Oceans Canada - Freshwater Institute)
Movement and diving of northern Hudson Bay narwhal: relevance to stock assessment and hunt co-management
Justine Hudson, Honours Undergraduate Student (University of Winnipeg)
Alexandra Beatty, Masters Student (University of Alberta)

Alyysa Bohart, Masters Student (University of Alberta)
Karyn Booy, Masters Student (University of Manitoba)
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Ellyn Davidson, Masters Student (University Centre of the Westfords)
Maha Ghazal, Masters Student (University of Manitoba)
Krista Kenyon, Masters Student (Centre for Earth Observation Science (CEOS))
Wesley Ogloff, Masters Student (University of Manitoba)
Ron Togunov, Masters Student (University of Alberta)
Michelle Viengkone, Masters Student (University of Alberta)
Spatial genetics of Hudson Bay polar bears
Thea Bechshoft, Post-Doctoral Fellow (University of Alberta)
Nick Pilfold, Post-Doctoral Fellow (University of Alberta)
Corinne Pomerleau, Post-Doctoral Fellow (University of Manitoba)
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Northern HQP

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ABSTRACT

Arctic marine ecosystems are ecologically and socio-economically vital and yet are threatened by anthropogenic global climate change. Marine mammals are an important resource for Inuit culture and economy as well as important ecosystem components across the Canadian Arctic. This project uses novel techniques to investigate the impacts of a warming Arctic on marine mammals to deliver non-invasive tools for northern community adaptations to global warming relative to sustainable local marine mammal indigenous subsistence hunts and traditional way of life. A core research team of experienced scientists with many years of northern-based community driven activities will continue to build on strong collaborations with other researchers involved in physical, biological, and social sciences as well as with our Northern and Inuit partners. We will study the coupling between physical environments, particularly sea ice dynamics, climate indices, thermodynamic processes, and marine mammal populations to better understand how arctic marine systems are responding to global warming. In particular, we will quantify changes in arctic marine mammal reproductive success, condition, survival, status, and ultimately how they respond to ecosystem changes, including the arrival of new marine mammal species from temperate regions. We will focus on inter-agency and international partnered research projects on all arctic marine mammals (polar bears, walrus, ringed seals, bearded seals, beluga, narwhal, bowhead, and killer whales) by (1) mapping chemical signals through ecosystem food webs, (2) modeling the effects of changes including predation and regime shifts, (3) studying emergent ecological responses such as disease and invasion by competitors, (4) conduct species-level extinction risk analysis, (5) build community-based monitoring programs that provide marine mammal and food web tissues for lab-based analyses (genetics, proteomics, fatty acids, stable isotopes, indicator chemicals, stress hormones, contaminants, amino acid compounds).

This project will examine global warming and the effects on water-based mammals in the Arctic and research will answer:

- How will marine mammals adapt to global warming – and what are the possibilities for future survival?
- What is the relationship between warming temperatures and the habitats of polar bears, seals, and whales?
- What are the potential effects of global warming on reproduction, and how many mammals will survive?
- What will be the effects of changes on northern communities and Inuit lifestyle?
- How can we reduce the effects of these changes and shelter the people and animals into an uncertain future?

Several areas of mammal health will be studied, including diet, diseases, contaminants, and stress. Satellite tracking, tissue samples from local hunters, genetic and population modeling, are the methods that will be used to understand change. Knowing how polar ecosystems may change with global warming will help to develop strategies for conservation and species management. It is important to recognize the changing distribution and numbers of Arctic mammals. Northerners depend on these species as a food source and as an integral part of their unique culture. Research results will help Inuit communities adapt to changes to marine mammal distribution and abundance while preserving their cultural lifestyle.

KEY MESSAGES

- Marine ecosystems are threatened by anthropogenic climate change, and the Arctic is already experiencing pronounced warming and changes in sea ice dynamics (Bluhm et al. 2008, Laidre et al. 2008).

- Arctic marine mammals (seals, whales, and polar bears) are vulnerable to these ecosystem changes through direct impacts like habitat loss (for example, sea ice as a platform for reproduction and hunting) and indirect impacts, such as changes in prey and predator distribution and abundance.
- Our research incorporates a mix of scientific methods and Inuit Qaujimatuqangit (Traditional Ecological Knowledge) to understand how climate-induced changes to food web structure, disease prevalence and contaminant levels, and invasion of southern competitors and predators will impact Arctic marine mammal abundance and distribution.
- Our project relies on strong collaborations with Northerners through community-based monitoring programs that provide tissue samples and research partnerships in all aspects of our field research programs.
- Our integrated research approach is providing a greater understanding of links between the Arctic environment and healthy marine mammal populations, which will ultimately inform management strategies for conserving marine mammal populations and socio-economic sustainability of northern communities in the face of Arctic climate change (Williams et al. 2008, Gagnon et al. 2009, Laidre et al. 2015).

OBJECTIVES

The central emphasis of our research is to better understand how sea ice and other environmental variables are coupled with marine mammal population demography, with the end goal of determining how marine mammal populations will respond to Arctic climate change. More specifically, we are:

- quantifying environmental linkages with changes in marine mammal health, distribution, and abundance. We are examining how reproductive success, condition, and survival are related to sea ice and other habitat characteristics;
- employing a suite of analytical technologies such as satellite telemetry, chemical dietary proxies (e.g. stable isotope and fatty acids), genetics analyses, and disease and contaminant profiling to understand ecological links among focal study species and their environment;
- training and engaging Northern communities as an extended network of on-site collaborators (e.g. community-based monitoring of sample and data collection), and incorporating Inuit Qaujimatuqangit as a complement to science-based methods;
- developing statistical and mathematical models that integrate data on focal species with climate, oceanography, and sea-ice data to identify species sensitivities to particular habitat variables; and
- quantifying the direction and species-specific consequences of regime shifts and other ecosystem changes related to a warming Arctic ecosystem.

KNOWLEDGE MOBILIZATION

Our group will mobilize knowledge through public outreach activities and northern community meetings. For example, many graduate students in Winnipeg are participating in the annual Arctic Science Day at Fort Whyte Alive, where they will interact with junior high and high school students. The goal for these students to obtain hands on exposure of the various aspects of Arctic research so that they can both further understand what research entails and perhaps be inspired to become further involved in research of some kind in the future. The education team at the Assiniboine Park Conservancy will use the ringed and harbour seal behaviour study results to teach guests about research and introduce them to animal behaviour research as part of the Arctic program at the zoo.

Community visits to Arviat and Pond Inlet early in 2017 to discuss marine mammal sample collections, to share results from previous research (aerial surveys, research related to sample collections), and to propose seal related research activities for the coming year (aerial surveys, sample collections, seal tagging), as well as to answer any questions or concerns from HTO board members. Meetings with HTO managers and discussions with local field guides takes place regularly during field activities in communities harboring research programs. Narwhal habitat selection results will be translated (English – Inuktitut) into posters and sent to the Hunting and Trapping Organizations of Arctic Bay and Pond Inlet, which were involved with equipping the narwhals with satellite transmitters. Bowhead knowledge mobilization is ongoing as monthly emails containing most recent maps of bowhead movements are distributed to community HTOs, funding partners, and colleagues. Distribution of satellite tracked polar bears continue to be disseminated weekly to appropriate government (e.g., Nunavut biologists, Manitoba biologists, conservation officers), indigenous groups (e.g., Nunavut Wildlife Management Board), and community members and is disseminated to a public audience using Twitter @ AEDerocher.

INTRODUCTION

Climate change in the Arctic, where considerable warming and shifts in sea ice dynamics are already occurring, will have important impacts on arctic marine mammals. Direct impacts of sea ice loss will be pronounced for species like ringed seals that require ice for pupping, and polar bears that acquire much of their food hunting on the ice. Other species, such as bowhead whales and belugas, may be affected indirectly by changes in prey abundance or distribution as the Arctic marine ecosystem shifts from one that is dominated by ice-algae to one characterized by more pelagic species. All arctic marine mammals will likely experience challenges posed by greater disease prevalence and competition from ecologically similar species that currently range further south, and greater predation by killer whales as they expand their presence in an increasingly ice-free Arctic. Identifying species' vulnerabilities to a changing Arctic marine ecosystem will allow for development of adaptation and mitigation measures for Northerners who are culturally and economically dependent on healthy populations of Arctic marine mammals.

Our research builds on data collected during previous ArcticNet funding cycles, and primarily addresses how various aspects of marine mammal demography (population dynamics), distribution, and health are linked with environmental variables, particularly sea ice. We are focusing on Arctic seals (ringed seals, *Pusa hipsida*; bearded seals, *Erignathus barbatus*; and harbor seals, *Phoca vitulina*), whales (beluga, *Delphinapterus leucas*; narwhal, *Monodon monceros*; bowhead whales, *Balaena mysticetus*); and polar bears (*Urus maritimus*) to answer questions such as:

- (1) How will marine mammals adapt to global warming – and what are the possibilities for persistence in space and time?
- (2) What is the relationship between warming temperatures and marine mammal habitats?
- (3) What are the potential effects of global warming on reproduction and survival?
- (4) What will be the effects of changes in marine mammal populations on northern communities and Inuit lifestyle?
- (5) Can non-invasive samples provide early indicators of environmental change?
- (6) How can we reduce the impacts of these changes on Arctic peoples and marine mammals?

We are collecting detailed empirical information and Inuit Qaujimatuqangit (Traditional Ecological Knowledge) on marine ecosystems from throughout Canadian Arctic. Links between key ecological components of the study (e.g. diet, foraging habitat, species distributions) are being integrated using chemical analytical methods (e.g. stable isotope and fatty acid profiles to infer food web structure) and satellite telemetry to identify critical habitat features and broad distribution patterns. Impacts of diet or habitat shifts on animal health are being investigated by analysing steroid hormone levels as a proxy for stress, and contaminants analysis to track pollution and uptake into marine mammal tissues. Genetics profiling is allowing us to estimate population size and structure, and will allow us to assess trends in arctic marine mammal abundance. As a complement to empirical data collection, we are also gathering Inuit Qaujimatuqangit, or Traditional Ecological Knowledge, on marine mammal diet, distribution, and behavior via interviews and conversations with Northerners.

Our approach combining scientific and traditional ecological knowledge is allowing us to assess how factors like reproductive success, condition, and survival are related to sea ice and other habitat variables. This information is essential for development of adaptive conservation and management measures for arctic marine mammals in the face of Arctic climate change, which will benefit Northerners who are culturally and economically reliant on these species. Our training and engagement of research partners in Northern communities (e.g. community-based monitoring programs in which tissue samples are collected by subsistence hunters) also facilitates knowledge transfer between researchers and community members, and contributes to building science capacity in the North.

ACTIVITIES

Many students were afforded the opportunity to use the ArcticNet Training Fund, which they all indicated as crucial in their graduate programs and thesis completion. Two students were able to acquire GIS experience, one student genetic statistical analyses and three students attended UNIS to further understand the Arctic ecosystem and the biological processes. We had a number of new students join our project and also had a few students continue to refine their analyses and explore previously acquired data.

Seals

Most seal studies during 2016-2017 primarily used tissues from the ongoing community based sample collections to investigate the foraging ecology of ringed seals. Diet studies used a variety of methods including; stomach contents, stable isotopes, and fatty acid analyses. Other studies were dedicated to reproduction, population assessments, and abundance surveys.

The following activities were completed in 2016-2017:

- Community based sample collections of ringed seal tissues continued and collected by local Inuit hunters from Arviat, Sanikiluaq, Kugaaruk, Resolute, Pond Inlet, Pangnirtung, and Naujaat (Repulse Bay). To date, tissue samples from 2016 were collected from approximately 203 seals as part of the community based sample collection program (Arviat=27, Sanikiluaq=66, Pond Inlet=16, Resolute=13, Pangnirtung=27, Repulse Bay=27, Holman=27, 2016 samples are still to arrive from Kugaaruk and Gjoa Haven).
- A collaboration with the Government of Nunavut Fisheries and Sealing Division and the Wildlife Officers stationed in communities allowed for samples from ringed seal pelts to be obtained from Hall Beach, Gjoa Haven, Pond Inlet, Qikiqtarjuaq, Kugaaruk, and Cape Dorset. More than 160 pelt samples have been collected as part of the ringed seal pelt sample collection program in 2016.
- Ringed and harp seal stomach contents from Pangnirtung were processed and prey identification is still in progress. Ringed seal stomach from Arctic Bay and Pond Inlet (n=103) were processed and prey identification is in progress.
- Muscle and liver samples from the same were subsampled, dried, and homogenized and lipid extracted for stable isotope analysis. Prey

samples (capelin) were also collected in the field and tissue samples used for stable isotope signatures.

- Semi-directed interviews with an interpreter were completed in Pangnirtung and Pond Inlet in the fall of 2016 to gather local Inuit knowledge on ringed seal foraging behaviour. Participants were active ringed seal hunters selected by the Hunter and Trapper Organizations.
- Investigated the foraging plasticity of arctic biota, specifically ringed seals and their potential to eventually adapt to changing environmental conditions. Scientific tools include stable isotopes and animal satellite telemetry. Using previously analyzed stable isotope data from ringed seal liver (~1200) and muscle (~1100) samples from across the Arctic, as well as satellite telemetry data from Resolute (n=7), Ulukhaktok (n=25), Igloolik (n=7), Sanikiluaq (n=80), Saglek Bay (n=13) and in Melville Bay, Greenland (n=13).
- Ringed seal blubber (n=300) was used to explore fatty acid composition differences between time periods and communities. Ringed seal prey species (n=200) were also used to determine significant differences between fatty acid composition of seven prey types.
- Ringed seal reproductive tracts collected from Hudson Bay communities were dissected to determine ovarian reproduction activity and pregnancy rates.
- Using harvested ringed seal tissues, we extracted DNA to determine gene flow between ringed seal groups across the Canadian Arctic and estimate abundance. Knowledge of ringed seal habitat was used to determine important landscape features to analyze. We used two models: (1) Isolation-by- Distance (IBD) model, great circle distance and (2) Least Cost Path (LCP) models; sea, bathymetry, and ice cover. We explored the use of estimating effective population size indirectly through genetic data in assessing abundance of ringed seals in Hudson Bay.
- Seal abundance and density surveys were conducted in Eclipse Sound, Milne Inlet, and Navy Board Inlet in June 2016. Surveys were flown in a DeHavilland Twin Otter (DH-6) equipped with four bubble windows and a camera hatch at the rear underbelly of the plane. A Global Positioning System (GPS) unit was used to log the position, altitude, speed and heading of the aircraft every second. The survey protocol included the use of visual observers as well as the collection of infrared video and colour photographs of the area directly beneath the plane.
- We investigated the potential difference in the level of vigilance of ringed seal and harbour seal in Churchill, MB in the spring of 2016. Additionally, we continued collecting data for estimating abundance during haul out for ringed seals and harbour seals. We tested new techniques to acquire aerial photography to help assess body condition, photo ID techniques, and non-invasive genetic sampling.

Whales

Studies on Arctic whales (narwhals, belugas and bowhead whales) as well as Arctic associated whales (sperm and northern bottlenose whales) in 2016-2017 focused on identifying important habitat and understanding the factors of habitat selection. Our narwhal study was focused on identifying important factors in narwhal winter habitat selection in Baffin Bay using satellite telemetry. Whereas Cumberland Sound beluga were monitored non-invasively using passive acoustic monitoring. Another non-invasive technique, drones, was used for the first time to record bowhead whale foraging behaviour in Cumberland Sound. Since little is known about sperm and northern bottlenose whale habitat selection, sighting data was compiled and mapped with associated environmental variables to predict future distributions. We are improving dietary studies of beluga by using amino acid compound specific methods.

The following activities were completed in 2016-2017:

- Sperm and northern bottlenose whale sightings were summarized for both the east and west sides of Baffin Bay and Davis Strait using GIS analytical tools.
- Bowhead whale fieldwork in Cumberland Sound in August included outfitting 11 bowheads with satellite-linked position and dive recording tags. As of December 16th 2016, five of these tags remained attached and continue to transmit, documenting movements in Cumberland Sound and their migration towards Hudson Strait for winter.
- Skin and Blubber biopsies from 87 Cumberland Sound Bowhead whales were obtained in August 2016.
- Bowhead whale preys (i.e., zooplankton) were collected and densities were estimated in areas where Cumberland Sound bowhead whales were foraging using an Optical Phytoplankton Counter, an AZFP Echosounder, and zooplankton nets. Environmental data was collected using a CTD to determine the physical characteristics of the water column.
- Unmanned Aerial Systems (UAS), or drones, for collecting high resolution aerial photographs of bowheads to use in photo identification studies were tested in Cumberland Sound in August 2016.
- Narwhal satellite telemetry data collected from Baffin Bay/northern Davis Strait narwhal were further analyzed to determine winter habitat selection focusing on environmental variables.
- Acoustic recordings of Beluga in Clearwater fjord collected from passive acoustic monitoring recorders in 2010 were analyzed to determine habitat use and establish contact call rates.
- Narwhal and beluga reproductive tracts collected by Inuit hunters were dissected and examined for pathology. There was a continued photo documentation of reproductive samples and ovaries and examination of ovarian reproductive activity.
- Beluga blood samples were collected from captive whales at the Georgia Aquarium in Atlanta Georgia along with their captive diet (i.e., fish and squid) which are being used for Amino Acid-Compound Specific Stable Isotope Analysis (AA-CSIA). These samples are currently being analysed for AA-CSIA at the University of California, Davis.
- Cumberland Sound beluga tissues (i.e., skin, muscle, and dentine collagen) were collected and are being analysed for AA-CSIA at the University of California, Davis.

Bears

Polar bear research in 2016-2017 focused on monitoring population changes in response to climate change. Primary objectives for 2016-17 were to continue long-term sample collection (i.e., hair, blood, nail, morphometrics) from free-ranging polar bears in the Western Hudson Bay and Beaufort Sea subpopulations. Most of our work investigates polar bear habitat selection and migration patterns using a variety of modelling techniques. We also continued to focus efforts on analyzing archived polar bear samples (i.e., hair and blood) for stable isotopes and cortisol levels, and also using other tissues along with hair to analyze mercury levels. Additionally, we are continuing to develop new less invasive techniques (i.e., microelements in hair using laser ablation techniques) to monitor polar bear populations.

The following activities were completed in 2016-2017:

- Field research was conducted in collaboration with Environment and Climate Change Canada and Manitoba Sustainable Resources in the western Hudson Bay polar bear population in September-November, 2016. GPS Iridium linked collars were deployed on 11 adult female polar bears to monitor movement ecology in western Hudson Bay. Additionally, 17 ear tag

- radios were deployed on polar bears handled by Manitoba Sustainable Resources to monitor dates of movement onto the sea ice and migration behaviour, and examine the increasing human-bear conflicts occurring in Nunavut in association with the longer ice-free period.
- Developed mathematical models to describe the movement paths of polar bears that suggest that some animals living in sparse environments may use strategies that are more complicated than those described by the standard random search models.
- Sample analyses continued with isotopes, cortisol, microelements, and mercury in the lab, with a large portion of time spent on sample preparation.

RESULTS

Seals

Stable isotope analysis of ringed and harp seals in Cumberland sound reveal that ringed seal niche width is larger than harp seals 97% of the time when muscle tissue stable isotopes are used, and 98% of the time when liver is used (Figure 1). Resulting in low niche overlap (3%) between ringed and harp seals when muscle tissue is used and a higher estimate (34%) when liver tissue is used. Preliminary stomach content analysis suggests that harp seals may consume fish more frequently than do ringed seals, but prey identification and quantification is still ongoing, and will further reveal the degree of niche overlap between the two species.

Stomach sample data from Arctic Bay and Pond Inlet were pooled across years and samples collected pre and post 2000 was pooled across communities. Percent prey abundance and frequency of occurrence were calculated for prey species based on otolith data only (Figure 2). Decreases of snailfish consumption over time were observed in ringed seal stomachs from Pangnirtung. In contrast, there was an increase of capelin consumption, which is a relatively new species to the area and now found in the stomachs of seals harvested in the 2000s. In Pangnirtung, we observed a decrease in Arctic cod frequency of occurrence in ringed seal stomachs, even though there has been an increase in the abundance of Arctic cod consumed. Conversely, in the northern region of Baffin Island, Arctic cod has both increased slightly in abundance and frequency of occurrence.

Stable isotope analysis further revealed a general latitudinal trend where the level of fish consumption and trophic position of ringed seals decreased due to increased prevalence of sub-arctic fish species and less trophic complexity in the zooplankton community at lower latitudes. The isotopic niche size also decreased with latitude for ringed seals and beluga whales. Individual specialization in ringed seals increased at lower latitudes as a likely response to large-scale spatial variation in ecological opportunity (i.e. prey species richness), which is higher at lower latitudes. Combining the stable isotope analysis with satellite telemetry, it was further revealed that individuals from higher latitudes spend more time traveling and less time foraging compared to individuals from lower latitudes.

Hudson Bay ringed seal and their associated prey were sampled for fatty acid analysis. Fatty acids compositions were significantly different between seven ringed seal prey species collected from Sanikiluaq (Figure 3), which will next be used in quantifying ringed seal diet using Quantified Fatty Acid Signature Analysis (QFASA). Ringed seals harvested from three Hudson Bay communities were significantly different from one another, reflecting temporal changes in fatty acid composition between time periods of rapid environmental change.

We found variation in ovulation and pregnancy rates among region, with lowest rates found in Sanikiluaq. Sanikiluaq also showed the most temporal variation of ovulation rates with a high of 100% in 2007 and low of 56% in 2011. With a one year lag time, the percentage of young of the year in the Sanikiluaq harvest followed

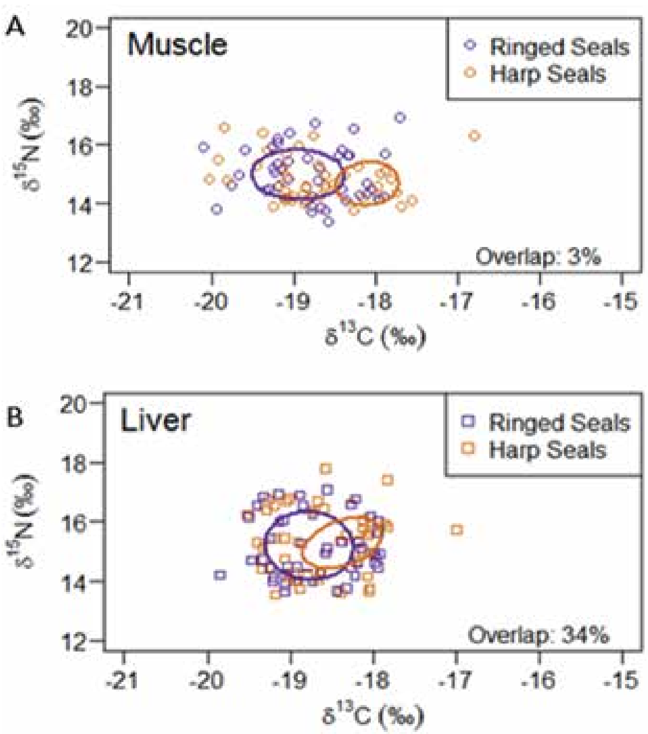


Figure 1. Isotopic niches of ringed and harp seals collected in Cumberland Sound, Nunavut from 2007-2015. Niche overlap refers to the percentage of ringed seal isotopic niche overlapped by harp seal isotopic niche.

a similar pattern to trends in ovulation rates from 2007 to 2011.

The aerial survey (Figure 4) of ringed seals generated 112 infrared video files, over 26,000 photographs, and over 40 hours of observer audio recordings. Analysis of data is ongoing and preliminary results are limited at this time. One important result that has become apparent in the early stage of analysis is that the use of infrared imagery (Figure 5) is a highly effective way of surveying seals hauled out on ice. The use of infrared video files allows us to relatively quickly determine which photographs to analyse for potential ringed seal observations. The relative success rates of the three seal detection methods (infrared imagery, regular photographs, visual observations) have not yet been determined, but initial analyses suggest that infrared imagery is the most reliable and efficient method of detecting seals on ice.

To assess whether demographic declines of Arctic species at the southern limit of their range will be gradual or punctuated, we compared large-scale environmental patterns including sea ice dynamics to ringed seal reproduction, body condition, recruitment, and stress in Hudson Bay from 2003-2013. Aerial surveys suggested a gradual decline in seal density from 1995-2013, with the lowest density occurring in 2013. Body condition decreased and stress (cortisol) increased over time in relation to longer open water periods (Figure 6). The 2010 open water period in Hudson Bay coincided with extremes in large-scale atmospheric patterns (NAO, AO, ENSO) resulting in the earliest spring breakup and the latest ice formation on record. The warming event was coincident with the highest stress levels and the lowest recorded ovulation rate and low pregnancy rate, few pups in the Inuit harvest, and observations of sick seals.

Whales

Sperm and northern bottlenose whale recordings were summarized for both the east and west sides of Baffin Bay(BB) and Davis Strait (DS), where both sides had high sighting density (Figure 7). The latitude ranges of the recorded sightings for sperm whales in BB-DS were comparable to the range at other locations in high latitude Atlantic waters. Spatial analysis results and a lack of records in northern regions of Baffin Bay suggest no change in the range when compared to past documentation in the area. Distribution patterns of sperm and northern bottlenose whales in BB-DS may be more closely linked to frontal zones and related prey distribution patterns than physical environmental variables. Distribution model results indicated predictor variables were able to accurately predict distributions of both species.

Bowhead whale movements and diving behaviour are being collected from satellite transmitter uplinks from 11 bowheads tagged in Kingnait Fiord, Cumberland Sound. By the end of September, six of the whales remained in Kingnait Fiord, while two whales had moved southeast, to smaller Fiords in Cumberland Sound. By the end of October, two whales remained

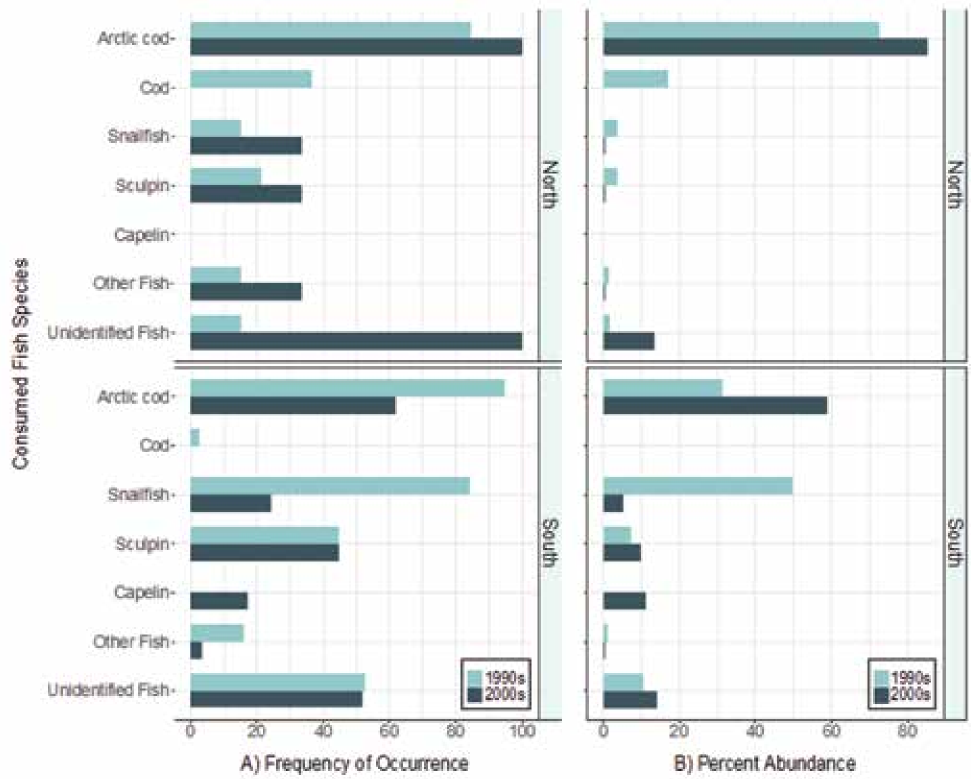


*Figure 2. A) Frequency of occurrence of vertebrate prey found in ringed seal stomachs; B) Percent abundance of vertebrate prey found in ringed seal stomachs. (North-1990s: n=33, North-2000s: n=3, South-1990s: n=38, South-2000s: n=29) *Fish listed as "Other" are dabbed shanny, eelpout, fourline snakeblenny, lumpsuckers, and sandlance.*

in Kingnait Fiord while three whales were making use of all smaller fiords along the northeast shoreline of Cumberland Sound. By late November, only four whales were providing good quality location data and all four had moved south to the fiords and inlets along the southwest shoreline of Cumberland Sound. By mid-December, five whales had provided good location data, with three whales making their way south along the coast of the Hall Peninsula, while two whales remained just outside the mouth of Cumberland Sound. As of January 4, 2017, six of the eleven transmitters deployed were still providing data (Figure 8). Three of the tagged whales had entered their wintering grounds in Hudson Strait, while three whales remain near the mouth of Frobisher Bay.

Narwhal habitat analyses revealed that bathymetry and floe size were most influential in narwhal winter habitat selection in Baffin Bay. Areas with bathymetric depths <1 km were avoided, whereas and areas with bathymetric depths 1.5 – 2 km were selected by narwhal. Additionally, narwhals selected for both areas with 0-35% ice concentration, as well as >95% ice concentration. Narwhals avoided land fast ice, and selected for ice floe sizes ranging between 0.5 km to 10 km. No sex differences were seen in winter habitat selection. Overall this meant that narwhals are highly specialized to survive within multiple sea ice types. They are primarily targeting areas with high prey densities regardless of the mobile pack ice or open water above them.

Preliminary analysis shows a clear pattern of movement and number of vocalizations for belugas in Clearwater Fiord of Cumberland Sound. Combining results from the detector with results from manual

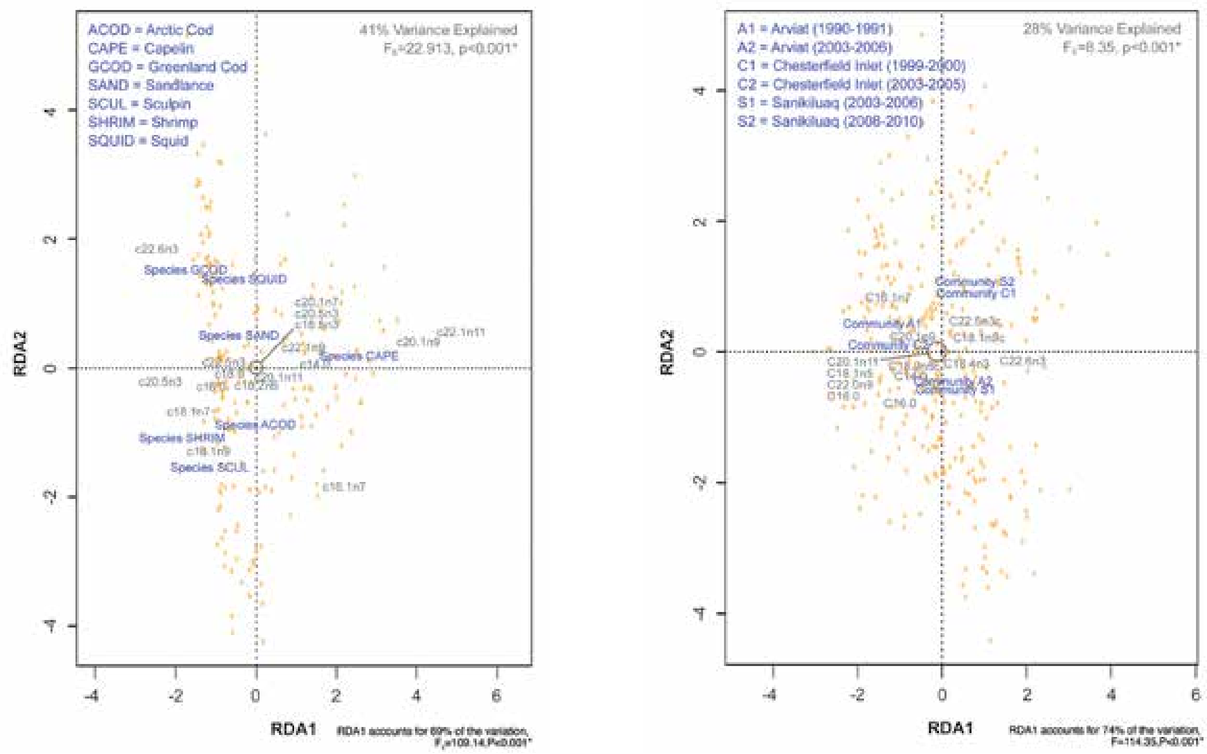


Figure 3. Redundancy Analysis of seven ringed seal prey species (n=200) collected from Sanikiluaq, Nunavut using the 18 most abundant fatty acids (left) and ringed seals harvested (n= 313) from three Hudson Bay communities using the 18 most abundant fatty acids (right).

detection indicate that automatic detection is a viable method by which to analyze large data sets obtained from passive acoustic monitoring devices (Figure 9).

Initial results from narwhal reproductive assessment indicate that ovarian reproduction activity (OVA) has declined in Baffin Bay narwhal between 1980 and 2005. Moreover, this population shows a higher pregnancy rate for the 1990's compared to 1982, which may correlate with lower counts of pathological cases during this time. No pathology results could be generated from data analysis of low-Arctic (Northern Hudson Bay narwhal population) due to insufficient sample numbers. Our results of beluga reproductive data analysis indicate a difference in ORA between the Hudson Bay and Cumberland Sound beluga populations. No noticeable change in ovarian activity for the Hudson Bay beluga was observed from 1989 to 2015 compared to an increase in ovarian activity for Cumberland Sound beluga from 1989 to 1997. Further, both groups show a strong correlation between age/length and ORA, but more pregnant females were present within the Hudson Bay beluga group compared to Cumberland Sound during the 1990's. Moreover, a one-year age difference in onset of age of sexual maturity was recorded between Hudson Bay and Cumberland Sound with Hudson Bay female beluga being shorter at time of age of sexual maturity compared to Cumberland Sound females. Within Hudson Bay beluga, a decline in pregnancy rate could be inferred with the 2000s compared to the 1990s.

Bears

We developed mathematical models to describe the movement paths of polar bears that suggest that some animals living in sparse environments may use strategies that are more complicated than those described by the standard random search models. Our results found that movement models that incorporate factors such as the perceptual and cognitive capacities of animals provide improved fit to data.

We investigated adult female habitat selection in Hudson Bay, and there was a high degree of Individual variation, a significant component of habitat selection. Selection changed across seasons and was most variable among individuals during the freeze-up and break-up seasons.

Migration patterns of polar bears in Hudson Bay corroborate studies that found thresholds of >50% sea ice concentration are necessary to be suitable polar bear habitat. We found that continued periods (e.g., days to weeks) of exposure to suboptimal ice concentrations during seasonal melting were required before bears migrating to land. Time-to-event models demonstrated that the bears made decisions based on an accumulation of knowledge from the seascapes they moved through and not simply the environment they are exposed to at the time of a decision. Understanding migration behavior of polar bears is important for insight on the potential demographic responses to climate-induced environmental changes.

We further examined the frequency of long-distance swims (>50 km) by female polar bears in the Beaufort Sea and Hudson Bay using satellite telemetry. Long-distance swims have increased compared to earlier studies. Our results indicate swims ranged of between 1.3 to 9.3 days, with a median of 3.4 days. The median swimming distance was 92 km with a maximum of 404 km. We also found swimming was more common in the Beaufort Sea and related to the rate of pack ice edge retreat.

Incoming and outgoing mass of polar bears temporarily detained by Manitoba Conservation and Water Stewardship during the open-water period near the town of Churchill, Manitoba were analyzed for mass loss dynamics. We estimated time to starvation for subadults and adult males for the on-land period and found that at 180 days of fasting, 56%–63% of subadults and 18%–24% of adult males would die of starvation. Results corroborate previous assessments on the fasting limits of polar bears and the challenges that an increased ice-free season will bring to the western Hudson Bay population.

Single-nucleotide polymorphisms (SNPs) have emerged as a tool for detection of fine-scale population structure. SNPs were applied in three polar bear subpopulations (Foxe Basin, Southern Hudson Bay, and Western Hudson Bay). Using discriminant analysis of principal components, our analysis supported the presence of 4 genetic clusters. Population structure differed from microsatellite studies and current management designations, which illustrates the value SNPs in polar bear genetic research.

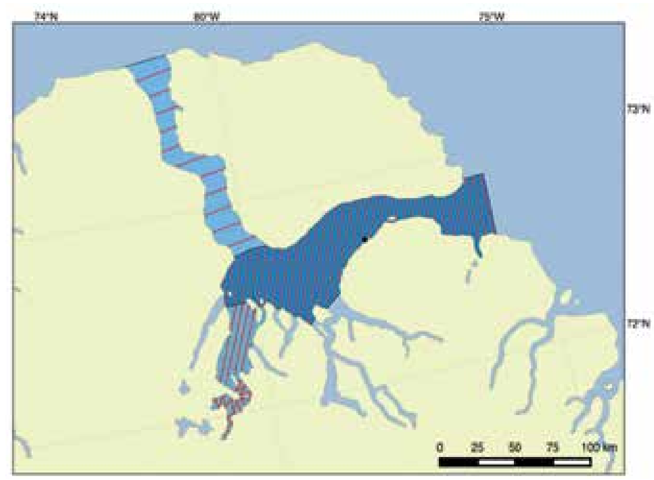


Figure 4. The survey area was divided into three strata: Eclipse Sound, Milne Inlet, and Navy Board Inlet.

DISCUSSION

Seals

Community based sample collection of seal tissues in the eastern Canadian Arctic is an important program which allows us to monitor various aspects of ringed seal health and ecology over time. A number of past projects have made use of the community based sample collections to reveal important findings on ringed seals in the Canadian Arctic (Chambellant et al. 2012; Chambellant et al. 2013; Ferreira et al. 2011; Young and Ferguson 2013, 2014; Yurkowski et al. 2011). Continued monitoring in key Nunavut communities, as well as expanding sample collection programs to new communities, increases the value of collections by providing new research opportunities in the form of long term and spatial comparisons. By working with the Hunters and Trappers Organizations in each of these communities, seal tissue samples were collected by local hunters during the regular subsistence hunt.

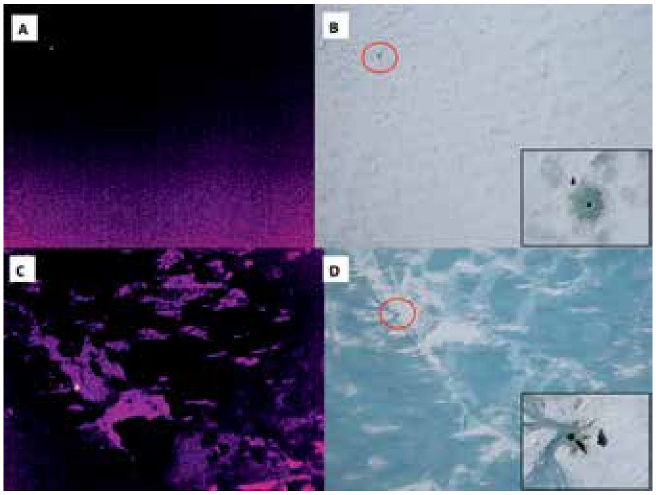


Figure 5. Examples of infrared imagery (A and C) and corresponding photographs (B and D) of ringed seals hauled out on ice during the 2016 aerial survey of Eclipse Sound, Milne Inlet, and Navy Board Inlet.

Harp seals, which have become very abundant in Cumberland Sound in recent decades (Hammill et al. 2015) appear to be utilizing similar resources to ringed seals, which have declined in recent decades (Diemer et al. 2011). When muscle tissue is used, overlap is very low, which may be due to the longer turnover period of muscle tissue (Vander Zanden et al. 2015), suggesting that stable isotope values obtained from muscle tissue may represent the diet of ringed and harp seals before harp seals have migrated to Cumberland Sound. Liver tissue, which has a faster turnover rate, may, alternatively, represent the diet of ringed and harp seals when the two species are sympatric. Ringed seals have a larger niche than harp seals when both tissues are used, suggesting that they are more generalist feeders. This may mean that during the time that harp seals inhabit Cumberland Sound; ringed seals may be able to shift their feeding to other sources and are thus not negatively affected by competition with harp seals. Further analysis of stomach contents will help to elucidate whether such a dietary shift occurs in ringed seals. Ringed and harp seals appear to utilize somewhat similar resources when they are sympatric, but further analyses are needed to assess whether age- and date-specific trends exist. Seals included in the above analyses range in age from 0 to 30 and kill month range from March to October, and this may account for some of the variation in stable isotope values. Inter-annual variation may exist as well, and this may also need to be factored into future analyses. Without studies determining the abundance and distribution of potential prey species in regions where ringed seal are harvested it would remain uncertain as to what degree ringed seal diet is affected by prey availability versus prey preference.

Individuals at higher latitudes undergo higher stochasticity in inter-annual sea ice dynamics, unlike lower latitudes, where inter-annual sea dynamics were more synchronous. Moreover, smaller individuals also spend more time transiting between habitat patches than their larger conspecifics due to competitive exclusion. These results reveal that ringed seals are responding to large-scale spatial differences in the availability and distribution of native and non-native prey species between the high- and low-Arctic, suggesting plasticity in their foraging decisions and spatio-temporal differences in food web structure across the rapidly changing Arctic.

Using genetic techniques to monitor ringed seals, we determined Least-cost path models explained patterns of genetic distance better than the great circle distance model (Figure 10). Bathymetry was the most influential environmental factor among the three least-cost path models, with shallow water facilitating gene flow and deep water acting as a potential barrier. This could be due to high levels of productivity that occur in shallow water attracting marine mammals to forage (Laidre et al. 2008). Ice was the least influential landscape feature on gene flow. This could be due to the dispersal patterns of ringed seals and their ability to travel great distances during the summer, when ice cover no longer acts as a barrier. There is a high level of gene flow among ringed seal populations in the Canadian Arctic. Least-cost path models explained patterns of gene flow better than the great circle distance model. Bathymetry was the most influential landscape feature, with deep water acting as a potential barrier to gene flow. Ice cover was the

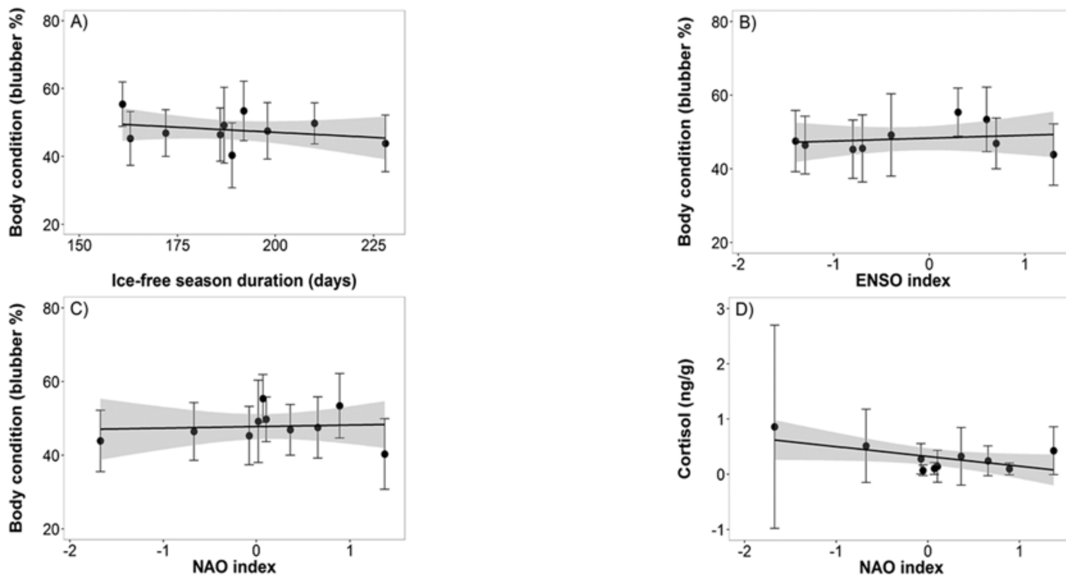


Figure 6. Linear regressions between ringed seal body condition and ice-free duration (A), body condition and El-Nino Southern Oscillation (ENSO) (B), body condition and North Atlantic Oscillation (NAO) index (C), and cortisol and NAO index (D).

least influential landscape feature. Furthermore, we used effective population size and effective number of breeders to infer trends in abundance (Figure 11). We have focused on a contemporary timescale and investigated the effect that seasonal variation in environmental variables had on population size and genetic parameters. Currently available contemporary estimators struggle to estimate effective population size when it is very large (~>10 000). However, effective population size can be estimated for smaller segments of the population if steps taken to account for potential violations of the assumptions of the estimator being used (e.g. overlapping generations, immigration, population substructure). This allows us to investigate the relationship between biotic and abiotic factors and the effective population size in a region.

Although analysis of seal aerial survey data is not yet complete and the relative success rates of the three seal detection methods (infrared imagery, regular photographs, visual observations) have not yet been determined, initial analyses suggest that infrared imagery is the most reliable and efficient method of detecting seals on ice. Similar conclusions have been

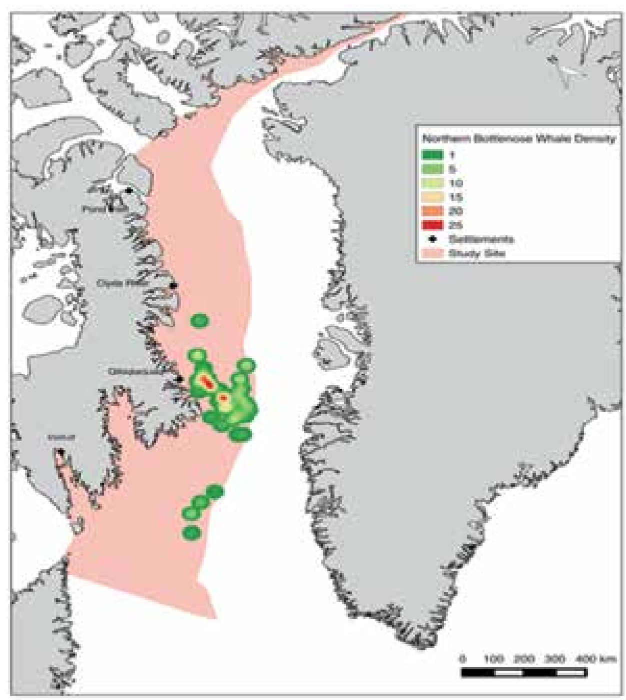


Figure 7. Example of mapping results - Heatmap of northern bottlenose density on the west region of the study site. Output from QGIS calculates sightings per area (30 km radius).

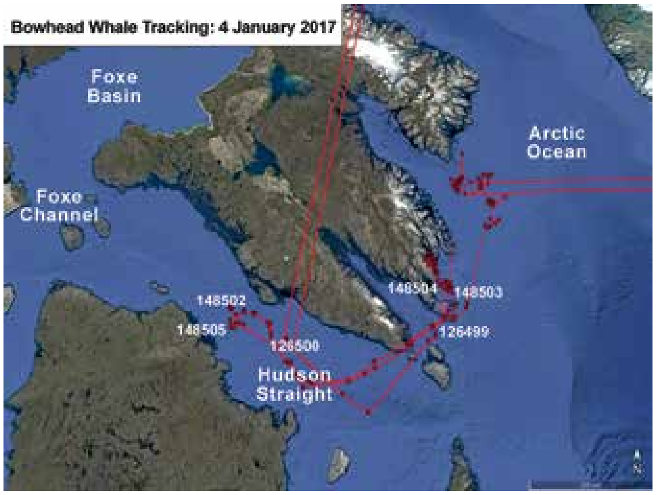


Figure 8. Cumberland Sound Bowhead whale locations on January 4 2017, tagged in August 2016.

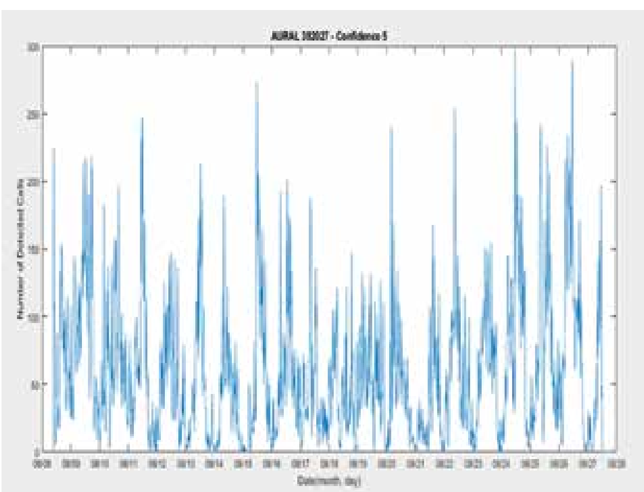
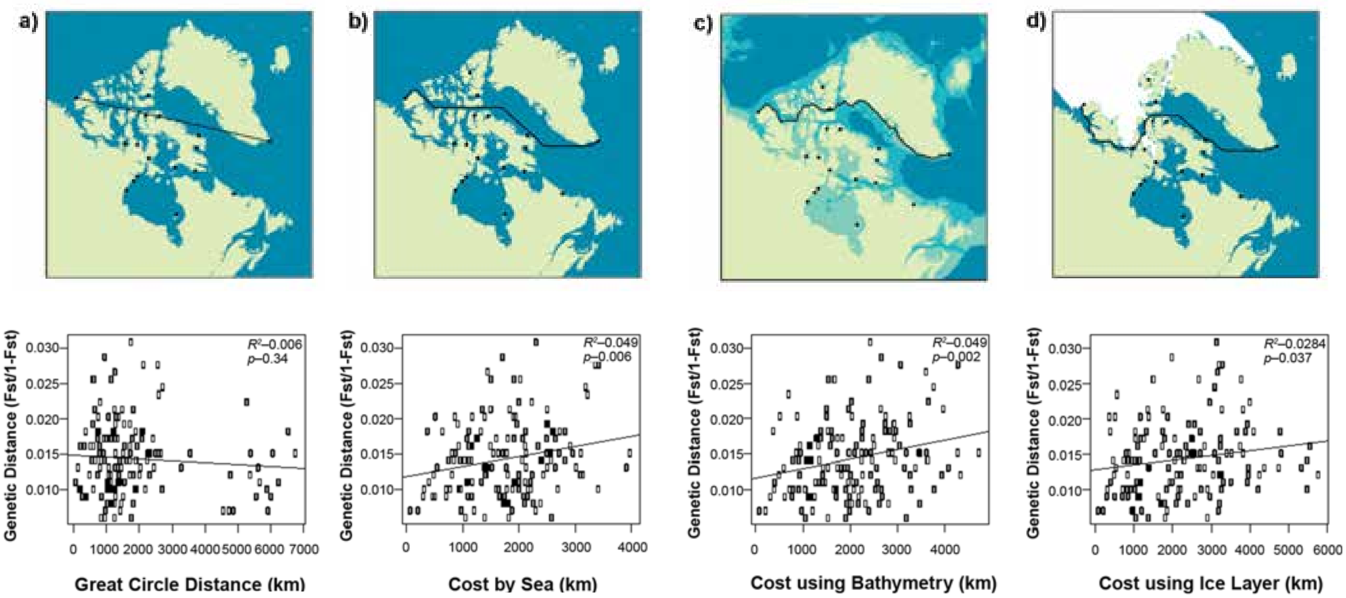


Figure 9. Number of calls detected via automatic detection program vs. date of recording for recording station AURAL382027, deployed in Clearwater Fiord of Cumberland Sound in 2010. From the figure it is evident that the presence of belugas fluctuates throughout the day and displays a pattern of movement and number of vocalizations. This figure also displays a title of "Confidence 5" which corresponds to the confidence level of the automatic detector in the results displayed, which in this case is 65% confidence.

reached by other research groups conducting surveys of ice seals using infrared technology (Conn et al. 2014). Further testing and development of infrared systems for conducting surveys of ice seals will lead to more efficient surveys requiring fewer survey team members and will improve density estimates through improved detection of seals.

Our vigilance behaviour studies suggest ringed seals are more alert (head up) than harbour seals. However, the actual amount of time dedicated to watching for predators was similar for both species. Ringed seals raise and lower their heads quickly to scan; while harbour seals raised their heads fewer times but remained alert for longer on average (Figure 12). Seals haul out for a number of reasons including: thermoregulation, resting, assisting in the moulting process, predator avoidance, social interaction, pupping, and nursing (London et al. 2012). For Arctic seals, there is a risk of polar bear predation while hauled out and therefore vulnerability to predators may strongly influence where and how long seals haul out as well as how vigilant they are while hauled out. We expect that other factors will influence seal vigilance including age, group size (Terhune 1985) and position in the group (Hamilton 1971), and weather (Finley 1985). If vigilance can be used as a proxy for predation risk then harbour seals move into the river for, and subsequently are able to reduce vigilance.

Considerable uncertainties exist with deciphering past patterns to determine possible cause and effect relationships among environmental variation, body condition, and their demographic responses. However, mounting evidence indicates endemic Arctic species, such as ringed seals, are under immense pressure from climate change and complex spatio-temporal shifts in ecology have subsequently resulted in decreased abundance as a harbinger of range shift. A recent episodic environmental event played a significant role in the condition of Hudson Bay ringed seals. Thus, managers need to be wary of climate change culminating in both a gradual decline in condition and unpredictable episodic events that when combined can have major abundance and distribution consequences.



Top panel: Example of the travel path between ringed seal populations in Sachs Harbor and Greendland using a) great circle distance, b) least-cost by sea, c) least-cost using bathymetry, and least-cost using ice cover. Dark blue represents deep water and light blue represents shallow water, green represents land, and white represents ice cover.

Bottom panel: Isolation-by-Distance and Least-Cost Path models. Pairwise Mantel test for genetic distance (Fst/1-Fst) as a function of straight-line distance (a). Pairwise Mantel test for genetic distance (Fst/1-F) and least-cost by sea (b), least-cost using bathymetry (c), and least-cost using ice cover (d).

Whales

The sperm and northern bottlenose whale study is the first to summarize the spatial characteristics of these two species in Baffin Bay and Davis Straight. This spatial information is crucial for making management decisions for arctic marine mammals including those for population-based conservation (i.e. determining critical habitat and drafting recovery plans for at-risk species) and for mitigating against impacts the consequence of climate change. Information on the abundance, seasonal and inter-annual spatial variability of prey species in the Baffin Bay and Davis Strait ecosystem are needed for both species in order to better predict future habitat use and distributions. This project highlights the need for information for the Baffin Bay –Davis Strait subpopulation of northern bottlenose whale as they are listed as data deficient by the IUCN and are believed to have a very low number of individuals in their population (Whitehead and Hooker 2012).

The bowhead dive data and movement data will benefit from combining information from the biopsy dataset obtained in previous years. The data collected in 2016 will prove useful for survey estimate correction for diving animals, analysis of dive behaviours relative to prey availability, and provide a better understanding of bowhead movements and habitat use. The biopsy samples collected in 2016 will add to previously collected samples to provide an updated abundance estimate for the Eastern Canada-Western Greenland bowhead population by using genetic mark-recapture methods. Genetic mark-recapture methods mark a number of individuals by determining their genetic fingerprint obtained from biopsy samples. At a later date, additional biopsy samples are collected and the proportion of marked and unmarked animals is determined. This information will then be used to estimate the total local population size. Monitoring bowhead whales using drones will greatly enhance our ability to develop a photo ID catalogue that will

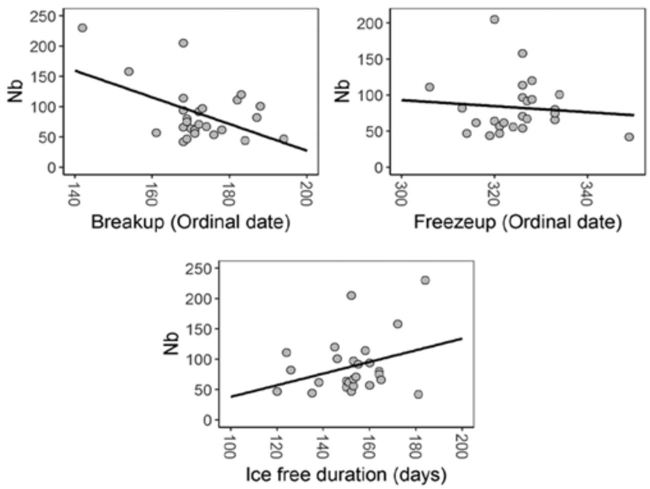


Figure 11. (Top left) significant relationship between the effective number of breeders (N_b) and the date of spring breakup, when a 5 year lag was applied to N_b relative to the ordinal date of spring breakup ($R^2 = 0.25$, $F_{1,24} = 8.01$ p-value = 0.009). There was no significant relationship between N_b and either ice free duration or fall freezeup when a 5 year lag was applied. A five year lag was applied because ice conditions likely have the greatest impact on mortality of young of the year seals, which influences N_b when they reach reproductive age in roughly five years.

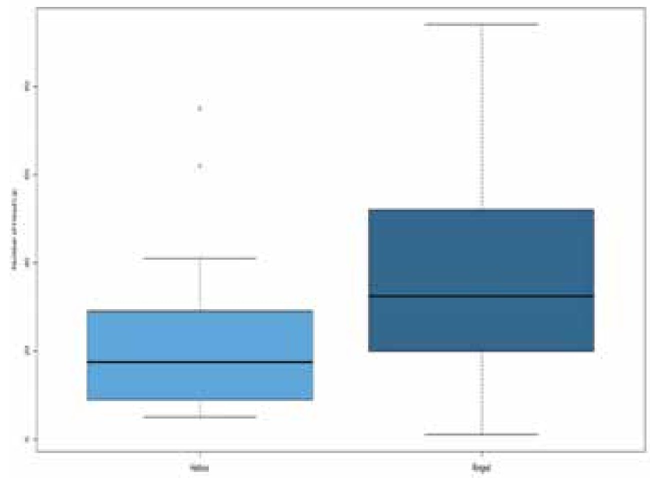


Figure 12. Difference in the number of head lifts of harbour seals and ringed seals during 2015 and 2016 observations. Ringed seals raised their heads significantly more than harbour seals ($F_{1,156}$=23.908, p<0.001). Although the length of time that the head was up and the number of times the head was raised were correlated, there was no significant difference between the species in the time spent with their head up ($F_{1,156}$=0.279, p=0.60).

allow for assessments of important life history traits and population demography including measures of body condition, growth rates, and calving intervals, and aid in estimating abundance. An updated abundance estimate of the Cumberland Sound bowhead whales is anticipated in 2018-19, to which our data will be an invaluable contribution.

Narwhals are one of the most sensitive species to climate change as they have a limited range, strict migration routes, high site fidelity, and few prey species. Baffin Bay narwhals winter in regions of Baffin Bay where there is <5% open water from January to April, they cannot break through thick pack ice, and are therefore susceptible to changes within the pack ice structure (Laidre and Heide-Jørgensen 2005a; Laidre et al. 2008). During this time Narwhals are intensively foraging on Greenland halibut at depths between 800 to >1400 m (Laidre et al. 2003; 2004; 2005b), and in areas with bathymetric depths 1.5-2.0 km where there is likely high prey densities (Jørgensen 1997, 2011; Treble 2015). There was no difference in habitat selection between sexes, which indicate that both sexes will be impacted similarly by changes within the sea ice structure. Results demonstrate that changes to winter prey populations resulting from climate change would greatly impact narwhals.

Beluga acoustic data will continue to be analyzed through an automatic detector, which has already shown promising results for determining the presence/absence of belugas in Cumberland Sound. Automatic detection similarly shows a distinct pattern in presence/absence of belugas that may indicate a pattern of movement between the locations where the hydrophones were placed. This research also has the potential to give greater insight into the poorly understood beluga whale communication repertoire while exploring new ways to detect and analyze passive acoustic monitoring recordings. Advancements in this field can allow for increased data collection via a non-invasive method, as well as maximizing efficiency in analysis of large datasets. Using this technology we can identify important habitat areas for beluga, and aid in understanding their communication.

Ongoing reproductive assessment of both beluga and narwhal show that reproductive activity and pregnancy rates are strongly correlated to whale age and body length. The observed preliminary trend suggests at least short-term variation may have impact on narwhal beluga ability to reproduce at rates recorded previously.

Bears

Analysis of archived samples from polar bears across the Canadian Arctic with priority on the Beaufort Sea and Western Hudson Bay populations will become increasingly important with ongoing climate change. Studies are designed to explore linkages to environmental change (e.g., Arctic Oscillation, sea ice metric). Developing an early-warning mechanism that precedes measurable demographic changes is our main priority, to better inform natural resource managers. We also aim to use less invasive methods, a priority for northern communities. We obtained samples from subsistence harvest to gain further develop linkages between climate change and polar bear health, but using multiple biomarkers.

CONCLUSION

In conclusion, with respect to marine mammal health, Arctic marine food webs are under immense pressure from a variety of factors including global pollution, hydrocarbon exploration and production, commercial fisheries, and climate change. Complex spatial-temporal shifts in ecological and subsequently demographic constraints are ongoing, that suggest that the arctic marine ecosystem is undergoing changes as a whole. It is to be expected that this trend will continue in light of the current and future Arctic climatic alterations and the continued and increasing presence of anthropogenic influences in the Arctic. With a changing Arctic ecosystem, the ecology of marine mammals adapted to sea ice habitat as an integral part of the ecosystem will also be affected. Altered population dynamics, abundance trends, migration patterns and new prey and predators are likely results. Expansion of ecological/biological investigations and wildlife health biomedical baseline studies, concurrent to already established demographic research on distribution and abundance for local management, and subsistence foods monitoring programs are therefore key to conservation success. The "Innovative Research on Monitoring Marine Mammals to Mitigate Impacts of a Changing Arctic" marine mammal research group plans to use the final two years of funding through ArcticNet centre of excellence to complete a final synthesis effort to bring to conclusion the ongoing long-term studies.

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THE POTENTIAL FOR NATURAL OIL SPILL BIODEGRADATION BY MICROORGANISMS IN CANADA'S ARCTIC MARINE ENVIRONMENT

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ABSTRACT

There is widespread concern and fear about oil spills in the Arctic. Society's appetite for energy, an increasing global population, and the lack of viable large scale renewable energy alternatives, means our reliance on petroleum will increase in the coming decades. Considerable oil reserves are estimated to exist in the Arctic (ca. 80 billion barrels may be extractable by conventional technology) and drilling for oil in the Arctic is poised to begin, with Canada's National Energy Board approving offshore drilling in the Arctic in 2011. Declining Arctic sea ice cover is projected to soon result in a completely open Northwest Passage allowing regular shipping transport. This will make the Arctic region susceptible to accidental releases of different types of hydrocarbon pollution, such as transportation fuels or crude oils being carried by tankers travelling through the Northwest Passage. The risk of accidental release of hydrocarbons in the marine environment was brought into focus by the Deepwater Horizon disaster in 2010; a silver lining of the Gulf of Mexico spill was the rapid mobilization of naturally present microbial communities that acted as 'first responders' in catalyzing bioremediation and significant mitigation of certain negative impacts associated with the spilled oil. The ability of microbes to degrade hydrocarbons is well known and is an example of the 'ecosystem services' that microbial communities can potentially provide to Canadian society and Canadian industries that produce and transport hydrocarbons. To fully realize these benefits the chemistry, physiology and ecology of the processes and environments involved need to be better understood. This project is structured around testable hypotheses about the marine microorganisms in the Canadian Arctic and their potential for the biodegradation of hydrocarbons. The project team comprises academics at the Universities of Calgary and Manitoba collaborating with researchers in the USA, Europe and major oil and gas companies with interests in the Arctic.

KEY MESSAGES

- With climate change and declining sea ice cover in the Arctic come increasing opportunities for industrial development and a higher frequency of shipping traffic, e.g., through the Northwest Passage. This elevates the risk of an oil spill or a spill of transportation fuel in Canada's Arctic marine environment.
- A silver lining of the 2010 Deepwater Horizon oil spill in the Gulf of Mexico was the rapid mobilization of naturally present microbial communities that acted as 'first responders' in catalyzing bioremediation and mitigating negative impacts on marine ecosystems. The deep water in this environment is permanently cold, suggesting a similar microbial response in the Arctic may be anticipated.
- Preliminary results from this project have revealed that bacteria in Canada's Arctic ocean are also capable of catalyzing biodegradation of hydrocarbons under cold marine conditions. Genomics has revealed that the Arctic bacteria are relatives of the Gulf of Mexico bacteria, but bear genetic signatures suggestive of being unique to the Arctic marine environment. Biodegradation under anaerobic conditions is possible but has not been able to be demonstrated in all Arctic locations tested so far.
- To test project hypotheses further, ongoing experiments using marine samples from across the Canadian Arctic are being evaluated for microbial responses to different kinds of contamination scenarios (e.g. diesel, bunker fuel, crude oil) under cold marine conditions. The degradation response to these different contaminant mixtures appears to vary between different regions of the Arctic. Samples are obtained aboard the research icebreaker CCGS *Amundsen*, and the project involves collaborations with other scientists in Canada, the United States and the EU.

- An important development and outcome of the project in 2016 was a successful application to Genome Canada for a new $10 million project GENICE: Microbial Genomics for Oil Spill Preparedness in Canada's Arctic Marine Environment. GENICE will be led by Casey Hubert (Calgary) and Gary Stern (Manitoba), and build on the momentum of this ArcticNet project. GENICE will run from 2017 through 2020.

OBJECTIVES

The main objective of the ArcticNet project is to combine field expeditions and laboratory tests, both on board the *Amundsen* and in our University labs, to test the four hypotheses outlined below:

Hypothesis 1: rates of crude oil biodegradation are not limited by low temperature in Arctic marine environments.

Hypothesis 2: the chemical nature of hydrocarbon mixtures limits biodegradation rates in Arctic marine samples.

Hypothesis 3: biodegradation of spilled hydrocarbons will be most rapid in areas near hydrocarbon seeps.

Hypothesis 4: contaminant baselines in sediment cores are influenced by biodegradation below the sea floor.

KNOWLEDGE MOBILIZATION

Summary of Project Knowledge Mobilization activities for 2016:

- Five presentations at scientific conferences and meetings:
    - » Noël, A., Hubert, C. (February 2016) "Hydrocarbon Biodegradation in Permanently Cold Marine Sediment". 2016 Gulf of Mexico Oil Spill & Ecosystem Science Conference, Tampa, Floria, USA.
    - » Noël, A., Hubert, C. (May 2016) "Predicting the microbial bioremediation response to marine oil spills in Canada". Canadian High Arctic Research Station Experimental Reference Area Meeting, Sidney, British Columbia, Canada.
    - » Noël, A., Hubert, C. (June 2016) "Anticipating microbial bioremediation responses to marine oil spills in the Canadian Arctic". Arctic Energy and Emerging Technologies Conference & Tradeshow, Inuvik, Northwest Territories, Canada.
    - » Noël, A., Hubert, C. (October 2016) "The presence and abundance of microbial hydrocarbon biodegraders and the potential for bioaugmentation in response to a possible Arctic oil spill in Cambridge Bay, Nunavut". Arctic Institute of North America - Northern Scientific Training Program Symposium, Calgary, Alberta, Canada.
    - » Noël, A., Hubert, C. (December 2016) Oral and Poster Presentation: "Marine microbial hydrocarbon degradation in the Kitikmeot region: are the microbial responses and communities the same as elsewhere in the Arctic?" ArcticNet Annual Scientific Meetings, Winnipeg, Manitoba, Canada.
- Interview with online, print, and broadcast media:
    - » September 2016: http://www.cnbc.com/2016/09/22/using-bacteria-to-clean-up-oil.html
- Meeting with Northern communities:
    - » June 2016: Arctic Energy and Emerging Technologies (AEET) Conference & Tradeshow, Inuvik, Northwest Territories.

Amy Noël attended the AEET Conference from June 13-15, 2016 and stayed for a scheduled day of meetings in Inuvik with Northern community stakeholders, industry, and leaders in Arctic oil and gas development. Previous AEET meetings focused heavily on oil and gas development; however, alternative energy sources (solar, wind, nuclear, and biomass) and the opportunities and challenges of those were highlighted this year. Planning and upgrading for energy conservation in Northern communities was also emphasized, as communities are trying to reduce dependence on diesel fuel. Energy exploration in the Beaufort Sea: There are significant discoveries in the deep Beaufort Sea but these represent high risk for extraction due to the complexity of working in and around sea ice. To overcome such difficulties, large oil companies are partnering on projects. Most projects would involve significantly higher capital investment and 2-3 years to drill (compared to single season drilling at non-Arctic sites). Also underscored were the gaps between policy makers in energy development in the North and key stakeholders affected by these decisions. Bioremediation of hydrocarbon spills in the Arctic: Most spills encountered are from day to day diesel usage, abandoned aviation fuel caches, and kerosene storage failure. *Ex-situ* aeration is the most commonly used technique for contaminated soils. Permafrost is considered as a barrier, though thawing/melting of the permafrost has not been considered with respect to movement of contaminants. Microbes and marine spills are not currently considered in commercial remediation efforts. The inevitability of a marine spill is generally accepted, but the main concern is over the effectiveness and impacts of dispersants in the marine environment, given the controversy and media coverage of dispersants used in the DWH spill in the Gulf of Mexico. There is definite concern over increased ship traffic; a new seaport will be built in the next 10 years out of Tuktoyaktuk. Project engagement: Amy Noël informally summarized research goals and preliminary results in meetings with stakeholders. The main goal surrounding engagement at this meeting was to inquire about best practices and listen to feedback about our project through engagement with Northerners. Research engagement activities can be quite complicated in Northern Communities, especially when projects such as this one span such large geographic area – there are different territorial governmental organizations, as well as different land claim territories to consider. Most Game Councils, HTOs, and Government groups meet quarterly, therefore future engagement activities should be planned to coincide with these meetings. Consultation is typically quite informal and researchers should provide food and drink for the events and advertise well in advance. Researchers should be sensitive to how they frame their research when communicating/engaging with Northerners – information flow should be bidirectional and researchers should come prepared with questions for Northerners. Researchers should always state when they intend to update the communities and return for meetings. Finally, Northern communities value skills development in youth – environmental monitoring is a priority and all aspects of monitoring (including microbiology, e.g., for baselines and future environmental effects monitoring) are of interest for engaging and training youth.

- One meeting with Northern research stakeholders:
  - » May 2016: Canadian High Arctic Research Station Experimental Reference Area Meeting, Sidney, British Columbia, Canada.

This meeting brought together scientists, funding organizations, and government groups to discuss research direction, results-to-date in the Cambridge Bay/Kitikmeot area, opportunities for collaboration, and fieldwork logistics and support for carrying out research activities at the Canadian High Arctic Research Station.

- One presentation to the general public:
  - » Noël, A. (July 2016) "Microbes, Mud, and Marine Oil Spills", University of Calgary Graduate Student Association's Research in the Pub Speaker Series, Calgary, Alberta.

Research in the Pub is an initiative that hosts University of Calgary graduate student research presentations in a fun, easy to understand, and casual environment at a downtown pub. The target audience is the general public, and events are free to attend. A university grant to support the Research in the Pub initiative was secured by Amy Noël (from this project) on behalf of graduate students from all disciplines across the University of Calgary campus.

INTRODUCTION

There is widespread concern and fear about oil spills in the Arctic. Society's appetite for energy, an increasing global population, and the pace at which viable renewable energy alternatives are coming online mean our reliance on petroleum will increase in the coming decades. Considerable oil reserves are estimated to exist in the Arctic (ca. 80 billion barrels may be extractable by conventional technology) and permits have been granted, however in the past year due to low oil prices and other factors, oil companies have abandoned or delayed plans for drilling, e.g., in the Beaufort Sea; this hiatus offers an ideal opportunity for science aimed at understanding the consequences of oil spills. Despite the hiatus related to oil production, maritime transportation through Canada's Arctic continues to increase. Declining Arctic sea ice cover is projected to soon result in a completely open Northwest Passage allowing regular shipping transport. This will increase the Arctic region's susceptibility to accidental releases of different types of hydrocarbon pollution, such as transportation fuels or crude oils being carried by tankers travelling through the Northwest Passage.

The risk of accidental release of hydrocarbons in the marine environment was brought into focus by the Deepwater Horizon disaster in 2010; a silver lining of the Gulf of Mexico spill was the rapid mobilization of naturally present microbial communities that acted as 'first responders' in catalyzing bioremediation and significant mitigation of certain negative impacts associated with the spilled oil. The ability of microbes to degrade hydrocarbons is well known and is an example of the 'ecosystem services' that microbial communities can potentially provide to Canadian society and Canadian industries that produce and transport hydrocarbons. To fully realize these benefits the chemistry, physiology and ecology of the processes and environments involved need to be better understood.

This project is structured around testable hypotheses about the marine microorganisms in the Canadian Arctic and their potential for the biodegradation of hydrocarbons. The project team comprises academics at the Universities of Calgary and Manitoba collaborating with researchers in Europe and oil and gas companies with interests in the Arctic.

ACTIVITIES

Geochemistry Methods

In 2016, we completed preparation (subsampling, freeze-drying, determining porosity) and analyses of radioisotopes in sediment cores collected from Scott Inlet (a known seep site) from aboard the CCGS *Amundsen* and began preparation and analyses of cores collected during a 2016 expedition aboard the RV *Nuliajuk* near Chesterfield Inlet and Wager Bay, Nunavut (Figure 1).

The activities of the radioisotopes ^{210}Pb and ^{137}Cs were counted in sediment core sections at the Environmental Radiochemistry Laboratory (ERL) at University of Manitoba. Sedimentation rates were then estimated by least-squares fitting the natural log of $^{210}Pb_{ex}$ profiles to outputs of a one dimensional two-layer advection diffusion model that accounts for both biomixing and compaction with depth. This approach explicitly takes into account the effects of bioturbation (biomixing), which may profoundly alter the depth distributions of tracers.

Hydrocarbon analyses were carried out at CEOS, University of Manitoba, on surface sections of cores from Chesterfield Inlet and Wager Bay. Hydrocarbons were extracted from sediments according to method USEPA3546. The extract was fractionated using silica gel

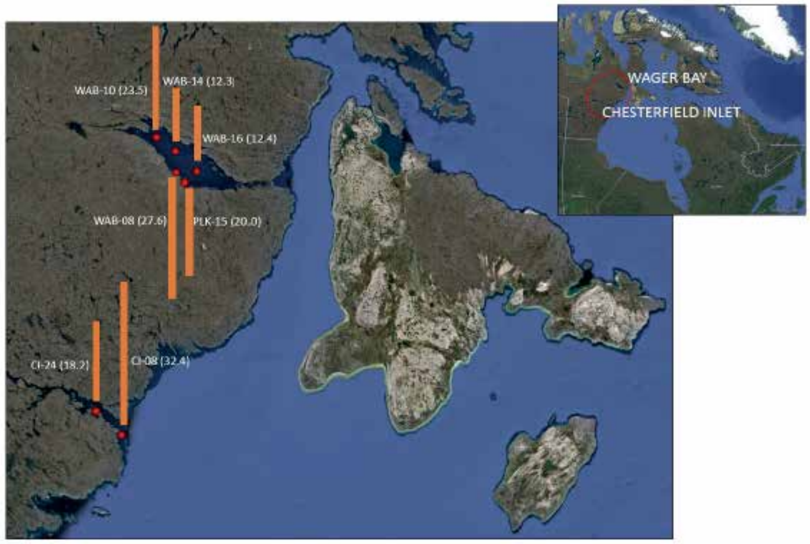

Figure 1. Sediment core locations near Chesterfield Inlet and Wager Bay, NU, sampled in 2016. Height of bars shows total concentrations of polycyclic aromatic hydrocarbons (PAHs) in top 2-cm sections of the cores. Because of intensified shipping activities and thus potential for future oil spills, this region will be a focus of future geomicrobiological studies to establish solid baselines.

chromatography via a modified version of USEPA method 3630C. Concentrations of individual compounds were quantified using a LECO Pegasus GC-HRT equipped with a high resolution time-of-flight mass spectrometer operated in Full Scan Mode (100-205 amu). Samples were analyzed in batches consisting of seven samples, one blank, one duplicate and a certified reference material. Samples were spiked with deuterated polycyclic aromatic hydrocarbons (PAHs) of known concentration. Target analytes were identified by comparing mass spectra and molecular properties to library compounds (NIST database, previous papers). They were also compared to the retention times and abundance of ions in the PAH calibration standards. Response factors of internal standards obtained during instrument calibration were used for quantification of compounds.

Geomicrobiology Methods

Sediment sampling using the box corer included bulk surface sediment bags for incubation experiments (mock oil spills) and ethanol-preserved aliquots of sediment for further genomic analysis (DNA sequencing for microbial community composition and biodiversity) at multiple stations throughout the Canadian Arctic (Figure 2). Sediment push cores were sectioned and ethanol-preserved for genomic analysis.

Water was collected on board using the CTD-Rosette at multiple stations. At each of the stations, bottom and surface water was collected and filtered on board for future molecular analysis.

Mock oil spills consist of small bottles in which artificial seawater is combined with marine sediment and either diesel, bunker fuel or crude oil in different concentrations. Bottles are incubated under either oxic (air in the headspace of the sealed bottles) or anoxic (90:10 N_2/CO_2 headspace) in the bottles. Incubations are conducted both at 4°C to mimic cold ocean conditions, and at room temperature (which promotes a more rapid microbial response). Some experiments are set up on board the *Amundsen*, kept at 4°C, and transported back to Calgary while still incubating in coolers with data loggers to record the incubation temperature. Incubations last from weeks to months, during which time the experiments are subsampled for analysis of the crude oil or fuel composition (via gas chromatography-mass spectrometry), oxygen and CO_2 in the headspace (via gas chromatography) and sulphate in the aqueous phase (via ion chromatography).

DNA extraction uses a modified bead beating approach either using commercial kits from MoBio (PowerSoil) or MP Biomedical (FastDNA Spin Kit) or using an in-house protocol. Using PCR, 16S rRNA genes from bulk environmental DNA extracts are amplified and purified for partial sequencing in the in-house Illumina MiSeq. Typically 10,000 reads are analyzed per sample, following quality filtering of the results.

So far, ROV sampling at seabed hydrocarbon seeps has not been possible. Requests have been made in previous years (through collaborators) and as part of this project in 2015, however without dedicated funding for ship time it has not been possible for this project's requests to be granted. Following fruitful discussions with the CSSF about ways to modify the ROV sampling infrastructure, fresh attempts were made in Baffin Bay in 2016 in collaboration with other ArcticNet projects and investigators (e.g. Evan Edinger) however problems encountered with the ROV prevented seabed sampling at hydrocarbon seeps. This will be attempted at Scott Inlet during Leg 2b in 2017. We have discussed possible joint applications for ship time (e.g. NSERC STAC) with Prof. Edinger and other ArcticNet NIs at Memorial University.

RESULTS & DISCUSSION

Geochemistry Results & Discussion

Modelling of radioisotope data in cores from Scott Inlet (a known seep site) reveal a slow sedimentation rate and significant influence of bioturbation (biomixing) on radioisotope profiles in the sediments. Coarse particles with low radioisotope activities imply mass transport processes rather than pelagic sedimentation affecting the coring sites. Scott Inlet is notoriously difficult to core because of the presence of a trough and steep slopes (GSC, personal communication). Coarse-grained sediments also imply that the sediments are a poor trap for hydrocarbons. Thus, low hydrocarbon concentrations may be expected. We conclude that these sediments probably do not comprise a good model system for studying natural hydrocarbon biodegradation potential, despite the natural seep in the area.

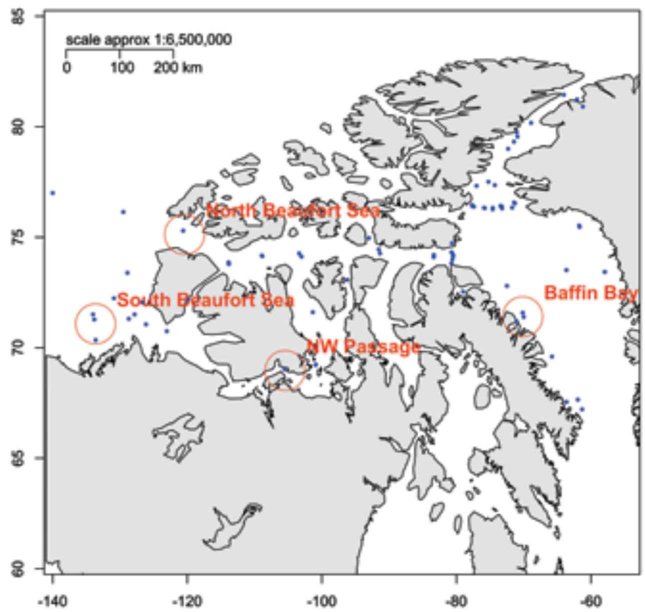

Figure 2. Sediment and water sampling sites displayed for the 2013-2016 CCGS Amundsen expeditions (blue dots), and the four areas targeted for hydrocarbon biodegradation incubation experiments (red circles) referred to in the text. Ice cores were also collected from the North Beaufort Sea area in 2016. The 2016 RV Martin Bergmann cruise involved high-density sampling in the NW Passage area.

Sediment cores from the Chesterfield Inlet and Wager Bay, Nunavut area show profiles of total ^{210}Pb that decrease exponentially with depth, consistent with expectations for steady-state sediment accumulation (profile governed by radioactive decay). Surface mixed layers are present in some cores, implying bioturbation. ^{137}Cs is present in only one of the cores analyzed to date; this core was collected from a nearshore basin which we expect receives significant terrestrial input. In the remaining cores, ^{137}Cs activity is at or near detection limits. Similar low ^{137}Cs activities have been observed previously in sediments from offshore regions of northwest Hudson Bay. Low precipitation and thus atmospheric deposition of ^{137}Cs that was released into the atmosphere during nuclear weapons testing in the 1950s and 60s may explain the absence of ^{137}Cs in these sediments. Without clear ^{137}Cs profiles in the cores, we will not be able to use ^{137}Cs to validate the sedimentation and mixing rates in the cores derived from ^{210}Pb. Nevertheless, the dated sediment cores will still represent a valuable natural archive from which contaminant and microbial baselines may be properly interpreted. The sedimentation rates will indicate the time scale over which hydrocarbons from various sources have been accumulated in the cores and an indication of whether there have been changes over time associated with, for example, changes in sources (increased ship traffic) or microbial degradation. Preliminary hydrocarbon analyses of surface sediment sections from the Chesterfield Inlet and Wager Bay, NU cores show total PAH concentrations averaging 12.3 to 32.4 ng/g.

In 2016, we also completed publication of results that help establish broad baselines for inorganic geochemical properties of Arctic shelf and slope sediments (Kuzyk et al., 2016). In this publication, we describe the early diagenetic conditions of sediments (e.g., oxic, anoxic, sulfidic) and characterize the concentrations and accumulation rates of various major and trace elements in 25 sediment cores from all along the North American Arctic Ocean margin. The results are very relevant to assessing the biodegradation potential of oil in throughout this domain.

Geomicrobiology Results & Discussion

Oxic Incubations

Sediments from the North Beaufort Sea (Station CB1), the Northwest Passage (Station 314) and a known hydrocarbon seep region in Baffin Bay (Scott Inlet; station PCBC2) were incubated with 0.1% v/v diesel, bunker fuel, or crude under oxic conditions. Higher levels of carbon dioxide production were observed for all contaminant mixtures compared to hydrocarbon-free (unamended) controls, indicating enhanced microbial activity in the presence of hydrocarbons. This suggests a capability of hydrocarbon biodegradation by cold-adapted Arctic marine bacteria. Diesel and crude oil amendment resulted in higher carbon dioxide production compared to bunker fuel, except in the case of Baffin Bay sediments incubated with diesel, which had significantly lower carbon dioxide production (Figure 3). The Illumina MiSeq platform was used to generate 16S rRNA gene amplicon libraries from DNA extracted from bulk sediment at the beginning, midpoint, and end of the incubation periods. Comparisons of microbial community compositions showed that shifts over incubation time were influenced by sediment source rather than hydrocarbon type (Figure 4). Further examination of amplicon libraries revealed enrichment of bacteria belonging to taxonomic groups known to include hydrocarbon degraders, such as the Alphaproteobacterial *Sphingorhabdus* spp. and the Gammaproteobacterial *Pseudomonas*, *Colwellia*, and *Cycloclasticus* spp. (Figures 5-6). Some of these lineages have been detected in oil spill contexts elsewhere in other parts of the world, including in the Gulf of Mexico following the Deepwater Horizon (DWH) accident in 2010. Further analyses will be needed at higher genetic resolution to assess the genotypic similarity between Arctic and Gulf of Mexico relatives (e.g. 'oligotyping'). Sediments from the Gulf of Mexico, provided by US project partners, will allow further testing of different metabolic capabilities in these different locations.

Anoxic Incubations

Incubation of sediment from Northwest Passage (Station 314) with diesel under anoxic marine conditions, i.e. where sulphate reduction is the predominant redox process, resulted in complete consumption of sulphate within eight weeks of incubation at 4°C. These microcosms turned black (indicative of sulphate reduction, i.e., produced sulphide forming FeS precipitate with iron in sediments; Figure 8), an additional line of evidence for the activity of cold-adapted sulphate-reducing bacteria (SRB) enriched

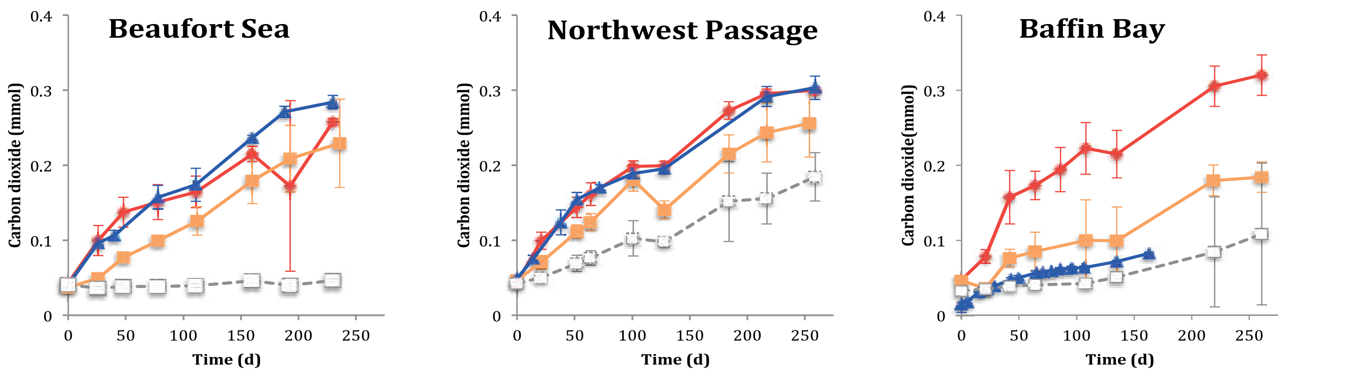

Figure 3. Enhanced microbial respiration (production of carbon dioxide) in Arctic marine sediment microcosms amended with 0.1% v/v/ diesel (blue), bunker fuel (orange), or crude oil (red) at 4°C relative to unamended controls (grey squares). Error bars represent standard deviation across triplicate incubations for each condition. This response is indicative of hydrocarbon biodegradation by cold-adapted sediment microbial communities.

in the diesel amendment. Despite strong evidence for diesel-driven sulphate reduction in this location, near Cambridge Bay, all other sediments from different regions of the Canadian Arctic incubated under similar conditions (five Beaufort Sea stations as well as station PCBC2 from Scott Inlet, Baffin Bay) did not display any sulfate reduction under identical experimental conditions (Figure 7).

For the positive NW Passage result, further investigation using DNA sequence analysis revealed significant enrichment of two Deltaproteobacterial genera, *Desulfofrigus* (enriched to 40% of the total microcosm community) and *Desulfotalea* (enriched to 25%) as shown in Figure 9. These two genera have previously been described as psychrophilic (cold-loving) SRB, but their ability to use hydrocarbon substrates has never been reported. There seems to be a difference

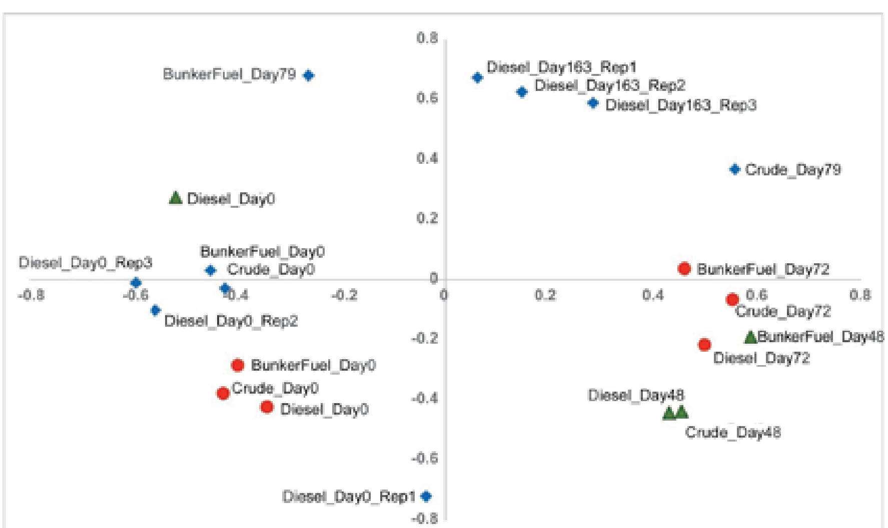

Figure 4. Non-metric multidimensional scaling of aerobic hydrocarbon biodegradation incubation 16s rRNA gene libraries (rarefied reads, Yue & Clayton Theta dissimilarity calculator; Stress: 0.242463, R-Squared: 0.743223). NW Passage (red circles), Beaufort Sea (green triangles), and Baffin Bay (blue diamonds) libraries clustered together at similar time points.

in microbial community composition and potential at Station 314 near Cambridge Bay, compared to stations surveyed from elsewhere in the Beaufort Sea and Baffin Bay. It will be interesting to explore with additional sampling and analysis whether and why this is the case.

Anoxic incubations from other locations that are apparently inactive (i.e. not showing any measurable loss in sulphate) were also analyzed using DNA sequence analysis. Similar community changes as observed in the Northwest Passage incubations were detected despite the lack of sulphate removal. *Deltaproteobacteria* increased in relative abundance after 236 days (Figure 10) but it remains unclear whether this is due to growth of these organisms or whether the shift is due to toxic effects of diesel causing the abundance of other groups to drop; cell counts or quantitative PCR will be used to further assess this result.

Vertical Redox Zonation

Preliminary analysis of Northwest Passage (Station 314) *in situ* microbial communities in 0-30 cm sediment depth profiles revealed that communities are different within 0-2 and 2-4 cm depth horizons, and change even more dramatically below 4 cm and again below 15 cm (Figure 11). This could reflect organic loading in this location and its effect on sediment redox zonation, i.e., oxygen penetration depth and the presence of the anoxic sulphate reduction zone. The presence of key hydrocarbon degraders identified in Northwest Passage incubations will be analyzed in these core depth profiles to determine their pattern of occurrence and whether they are prevalent enough to be detectable in *in situ* screening of this kind, or whether these hydrocarbon-degrading SRB (cf. Fig. 9) are low abundance members of the microbial 'seed bank' in station 314 sediments. Future box core sampling from RV *Martin Bergmann* will sample the upper 2 cm of the sediment at higher sampling resolution to assess this microbial community in greater detail.

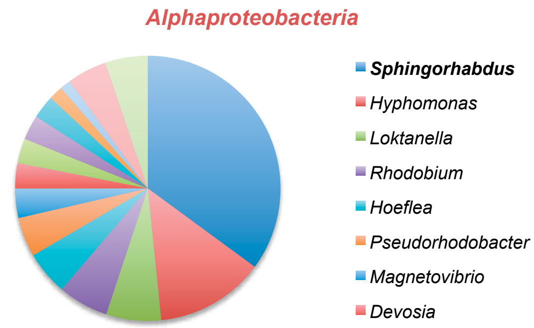

Figure 5. Sphingorhabdus spp. were the dominant Alphaproteobacteria enriched in Baffin Bay (Scott Inlet) sediment from station PCBC2 in the presence of diesel incubated at 4°C. Proportions shown are the mean relative abundance values from triplicate 16S rRNA gene amplicon libraries.

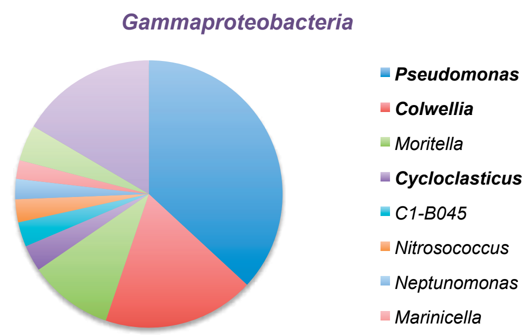

Figure 6. Pseudomonas, Colwellia, and Cycloclasticus spp. were the dominant Gammaproteobacteria enriched in the presence of diesel in Baffin Bay (Scott Inlet) sediment from station PCBC2 incubated at 4°C. These lineages include well-known hydrocarbon degraders from other low temperature marine habitats, including the Gulf of Mexico. Proportions shown are the mean relative abundance values from triplicate 16S rRNA gene amplicon libraries.

Water Column and Sediment Microbial Community Comparison

Figure 12 displays the microbial communities at the Class level for a vertical column of surface water, bottom water, and surface sediments in the Northwest Passage (Station 314). Sediment microbial communities were more diverse (Shannon distribution = 4.68) than the water column communities, where surface and

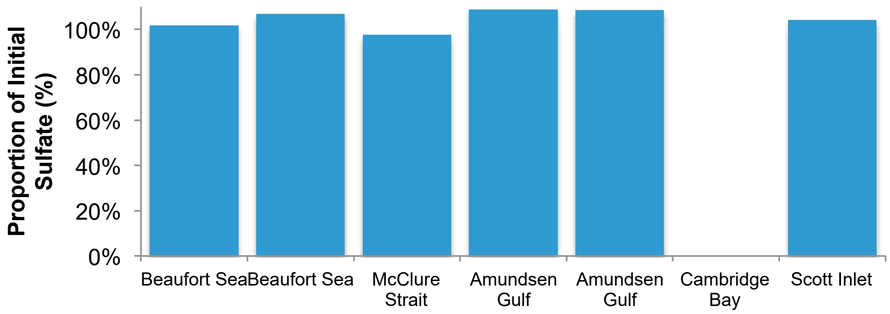

Figure 7. Eight-week incubations of seven different marine sediments under anoxic conditions in the presence of diesel only gave rise to sulphate consumption in Cambridge Bay sediments (ArcticNet station 314). For these triplicate incubations sulphate was completely consumed after eight weeks, suggesting anaerobic hydrocarbon biodegradation potential may be high in this region. Each bar reports the mean value from triplicate incubations.

bottom water samples had similar diversity (Shannon distributions = 3.10 and 3.66, respectively). The presence of *Flavobacteriia* decreased with depth while *Deltaproteobacteria* and *Bacteroidia* increased with depth. *Gamma*- and *Alphaproteobacteria* were present at constant relative abundance through the water column and sediment. With regard to putative hydrocarbon-degrading genera, 10 OTUs were detected, six of which were present in both water and sediment environmental samples: *Colwellia* (3 OTUs), *Oleiphilus*, *Thalassolituus*, and *Pseudoalteromonas* spp.. Though these OTUs were present in very low abundance in both sample types, they (and potentially others) could be key members of a 'seed bank' of microbial hydrocarbon degraders that could be relevant in the case of an accidental oil or fuel spill near Cambridge Bay. These OTUs will be compared for their relative abundance and sequences aligned with those derived from Northwest Passage contaminant-amended incubations (cf. Figs. 3-5 NW Passage results) to further validate their potential as biodegradation indicators.

Figure 8. Diesel amended microcosms of Cambridge Bay sediments incubated under cold anoxic conditions turned black after eight weeks (left), compared to no-diesel unamended controls (right). Six other diesel amended sediments from other locations (cf. Fig. 7) were similar in appearance to the controls (not shown).

CONCLUSIONS

Results to date confirm that hydrocarbon biodegradation under cold Arctic marine conditions is possible, and that some variability exists between regions and for different contaminant mixtures. Marine seawater and sediment samples have been incubated in different mock oil spill scenarios, revealing shifts in microbial communities and enabling identification of bacteria that are potential first responders capable of catalyzing hydrocarbon biodegradation in the event of an Arctic spill. Tests under both aerobic and anaerobic conditions have demonstrated evidence for biodegradation, though not in a consistent 'one size fits all' fashion, for the Arctic sites tested so far. Sediments from Chesterfield Inlet are being modeled to determine sedimentation rates and offer an opportunity for comprehensive baseline determinations that incorporate both microbial diversity and sediment geochemistry, including a chronological component.

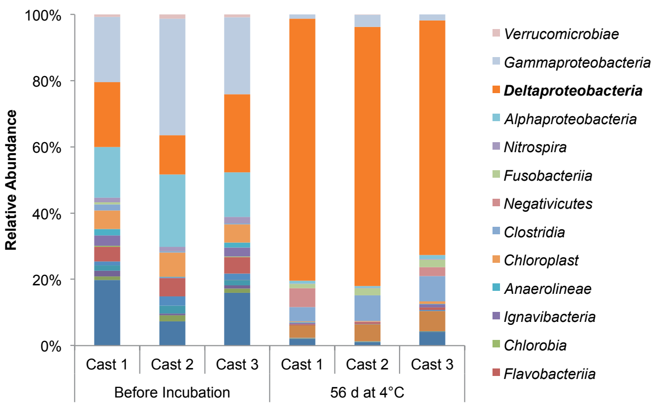

Figure 9. Illumina MiSeq 16S rRNA gene amplicon libraries were prepared for triplicate microcosms prepared using sediment obtained from separate, triplicate box core casts at station 314 near Cambridge Bay. The libraries indicate enrichment of cold-adapted Deltaproteobacteria after 56 days under cold anoxic conditions in the presence of diesel. Putative cold-adapted hydrocarbon-degrading sulphate-reducing bacteria affiliated to the genera Desulfofrigus and Desulfotalea were identified in this data when it was analysed at greater taxonomic resolution (data not shown).

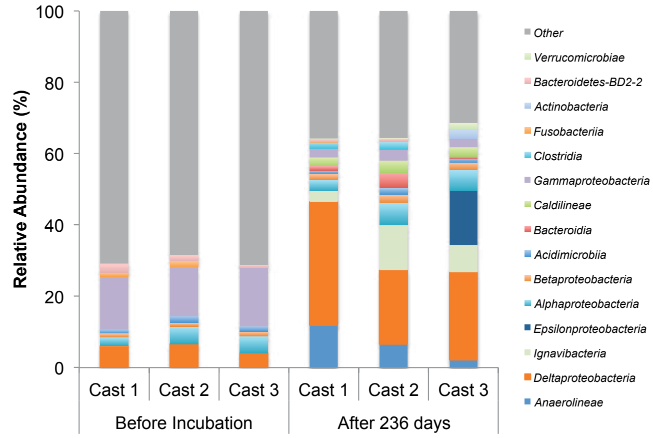

Figure 10. Changes in relative abundance at the microbial Class level after 236 days in anaerobic Baffin Bay sediment 4°C incubations with 0.1% v/v diesel. OTU assignments were performed using MetaAmp and the SILVA database. The 'other' group comprises all classes that were present in less than 1% relative abundance in all samples. An enrichment of Deltaproteobacteria is observed, however a corresponding drop in sulphate concentration was not observed in these microcosms.

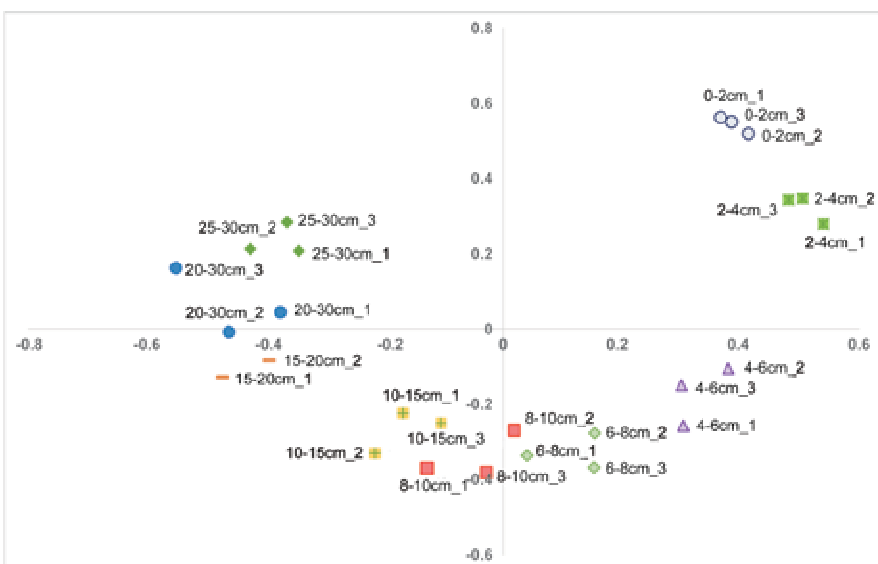

Figure 11. Non-metric multidimensional scaling of Northwest passage sediment core 16s rRNA gene librairies (rarefied reads, Yue and Clayton Theta dissimilarity calculator, Stress: 0.120484, R-Squared: 0.960856).

ACKNOWLEDGEMENTS

Dr. Hubert and Dr. Kuzyk wish to thank ArcticNet for its ongoing support of our benthic marine oceanography research and for assistance in establishing new Canada-based research on bioremediation of Arctic marine oil spills. We are grateful to the crew of the CCGS *Amundsen* as well as Keith Levesque at ArcticNet, 2015 chief scientists Roger François and Philippe Archambault, and 2016 chief scientist Louis Fortier, for their assistance and collaboration in obtaining samples for our project. We also wish to thank Adrian Schimnowski and the Arctic Research Foundation, as well as Prof. Brent Else at the University of Calgary, for their collaboration in our work around Cambridge Bay including the successful 2016 expedition aboard RV *Martin Bergmann*.

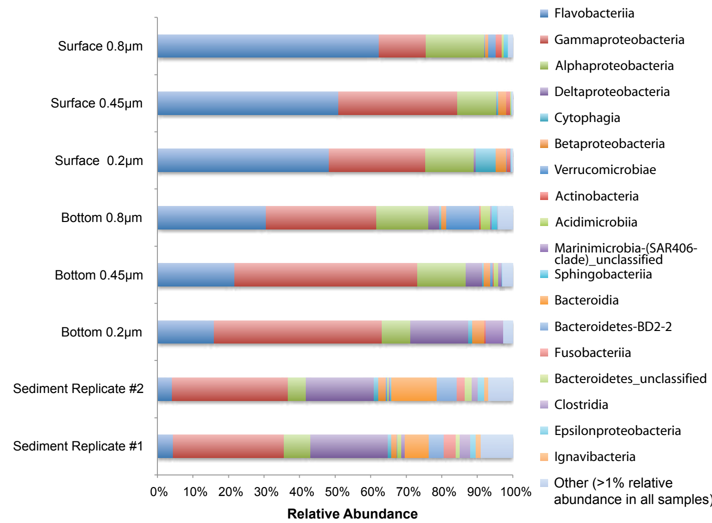

Figure 12. Differences in relative abundance of microbial classes between surface water, bottom water, and surface sediment in the Northwest Passage. OTU assignments were permformed using MetaAmp and the SILVA database. The 'other' group comprises all classes that were present in less than 1% relative abundance in samples.

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FRESHWATER-MARINE COUPLING IN HUDSON BAY: A STUDY OF WINTER ESTUARINE PROCESSES IN THE COASTAL CORRIDOR IN SOUTHEAST HUDSON BAY AND EFFECTS OF ENVIRONMENTAL CHANGE

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ABSTRACT

Hudson Bay, and in particular the southeast "coastal corridor" (between the Belcher Islands and the mainland), resembles a large estuarine system, receiving a tremendous amount of river runoff together with seasonal sea ice melt each summer. In the winter, when most of these freshwater inputs have been shut off, the salt in the seawater gets rejected as sea ice forms and seeps into the underlying water, making it saltier. Areas of open water such as polynyas and flaw leads act like 'ice factories', making ice very rapidly and thus releasing a lot of salt into the underlying water column. This process is very important because it causes the water to mix, thus replenishing the nutrients in surface waters and sometimes forming waters that sink down into the deepest parts of Hudson Bay. Although these are very important processes in Hudson Bay, and ones that may be impacted by hydroelectric development (which has shifted river discharge into the winter time) and climate change (which is shortening the period of ice cover), they are not very well understood because few studies have been done there in the winter. The lack of scientific data is becoming increasingly urgent because Inuit from local communities have observed that environmental changes in winter in southeast Hudson Bay seem to be already underway. In this study, a team of university researchers will collaborate with Inuit and Cree from five communities in southeast Hudson Bay to study the winter conditions and processes in the coastal corridor, where most of the freshwater travels (at least in summer). Through salinity and temperature profiling of the water column, measurements of currents, and application of freshwater tracers (analyzed in water and ice samples), we will quantify the amount and sources of freshwater present in winter, its distribution and its interaction with sea ice formation, mixing of the water column and deep water production. This scientific basis will provide insight into possible impacts of hydroelectric regulation and climate change in southeast Hudson Bay. The information will be accessible in near real-time by community partners through web-based platforms. It will also be communicated to scientific audiences and other stakeholders, and represents an important contribution to the ArcticNet Hudson Bay IRIS.

KEY MESSAGES

- The coastal corridor in southeast Hudson Bay is the key transporter of freshwater from major source areas (rivers) in southern Hudson Bay and James Bay, northward to Hudson Strait. In past years it was assumed that little freshwater remained in the region in winter. However, recent observations by Inuit suggested that oceanographic conditions may have changed.
- This project is collecting data to improve our understanding of how river runoff, tidal mixing, upwelling and sea ice are interacting to modify water masses and circulation in Hudson Bay; the physical, chemical and biological significance of those interactions; and the evidence for recent changes.
- During the winters of 2015-2016, we worked in partnership with Inuit and Cree from five communities in southeast Hudson Bay to obtain data during winter, a crucial period that has previously been neglected. We collected vertical profiles of salinity and temperature in the water column, time series of salinity and temperature at various depths, and measured currents. We also collected tracer data to distinguish between different sources of freshwater in this region, and data on ice and water to provide a direct evidence of freshwater balance throughout the year.
- The project has generated a large amount of new data about the freshwater distributions, and interactions between runoff, sea-ice melt and sea-ice formation. Our 2015-2016 results show considerable quantities of river water in the coastal corridor of southeast Hudson Bay in winter. A large river plume extends under the ice in northeast James Bay at the same time and surface salinity of James Bay outflow varied from

22 to 26 during the period of January-April 2016. The next steps are to work to confirm the specific source of river water in southeast Hudson Bay and to evaluate the interaction of this runoff with the local sea-ice formation cycle and other ocean processes to determine its physical, chemical and biological significance.

- This project is made possible by the excellent research partnerships we have established and continue to develop with Inuit and Cree from five communities in southeast Hudson Bay. The interactive mapping platform associated with the project (IK-MAP) facilitates the collaboration through straightforward and nearly real-time access to the field data. Ultimately, the results will be of interest to the scientific community engaged in studying environmental change in various Arctic areas as well as an important contribution to the ArcticNet Hudson Bay IRIS.

OBJECTIVES

In the second year of our project, we continued to make progress on the following objectives, as stated in our proposal:

1. Document the spatial patterns, temporal evolution and inter-annual variability in freshwater distribution in winter in the coastal corridor in southeast Hudson Bay.
2. Quantify the freshwater sources using tracers and calculate inventories of the components in the water column.
3. Characterize the deep water in Hudson Bay and gain insight into key sea ice formation and water modification processes and sites (e.g., polynyas), and interactions with freshwater distribution.
4. Evaluate whether offshore data collected from ships and moorings reflect conditions in coastal areas, which are of great importance to Inuit and Cree communities.
5. Promote knowledge exchange and provide information relevant to the concerns of citizens in the communities along the coastal corridor in southeast Hudson Bay.
6. Build collaboration in research activities and ultimately help increase the capacity of partner organizations and communities to collectively participate in and benefit from community-driven research initiatives.
7. Contribute to the goals and objectives of complementary research efforts, including the NSERC CRD project "BaySys", through strong communication and coordination of planning, cost-sharing of equipment, instruments, and information, co-participation of the research team in both projects.

KNOWLEDGE MOBILIZATION

The following activities have helped disseminate our research results in 2016:

- Using the Arctic Eider Society's on-line interactive mapping platform IK-MAP, results of more than 280 oceanographic deployments (e.g., conductivity-temperature-depth (CTD) casts) and ten moorings (including continuous observations of temperature, salinity and in places currents) have been made available in near-real time to all research partners and the interested public.
- Seven presentations have been made at five scientific conferences, including the Inuit Studies Conference, St. John's, NL; the ArcticNet ASM 2016, Winnipeg, MB; FAMOS 2016, Woodshole, MA; CMOS/CGU 2016, Fredericton, NB; and AGU 2016, San Francisco CA.
- Hands-on training in oceanographic monitoring/sampling methods and general scientific mentoring has been conducted with more than 35 Northern research partners and more than 15 youth across five communities.

- Community consultation meetings were completed in five communities, including Sanikiluaq, Inukjuaq, Umiujaq, Kuujjuaraapik, and Chisasibi.
- One meeting was held with Cree Nation Government decision-makers.
- Two in-person meetings and several conference calls were held with International eelgrass experts to build collaboration around researching eelgrass health in relation to altered hydrology and coastal oceanography.
- Contributed to development of the Arctic Sea Ice Educational Package: culturally relevant curriculum for northern schools (Nunavik region).
- Contributed to presentations and discussions and provided scientific context and background for the Hudson Bay Consortium meeting, Chisasibi, Nov 2016; this effort is focused on building collaboration and information sharing towards environmental stewardship goals for the greater Hudson Bay/James Bay region.
- Contributed to the Hudson Bay IRIS.

INTRODUCTION

The shallow Riverine Coastal Domain is a critical gap in our understanding of Arctic ecosystems (Macdonald, 2000; Carmack et al., 2015). The freshwater supplied by river runoff drives a contiguous coastal boundary current that is of key importance not only for physical and chemical processes that couple the terrestrial and marine environments but also a controlling factor for wildlife and human use. The Riverine Coastal Domain is also a focal point for environmental change, firstly because of its estuarine character, and secondly, because of the influence of the seasonal sea ice growth-melt cycle. Through influences on stratification, freshwater inputs and tidal mixing can alter the onset and rate of sea-ice formation. In turn, sea ice melt represents a second important source of freshwater to Arctic coastal systems, in addition to river water. Both freshwater sources are important in Hudson Bay and both have undergone change due to hydroelectric development and climate change.

The coastal corridor in southern and eastern Hudson Bay is a large Riverine Coastal Domain with similarities to coastal regions in the Arctic Ocean but also important differences. Because Hudson Bay is at the southern margin of the Arctic, it may undergo earlier and more rapid warming due to climate change than areas further north. Thus, the Hudson Bay system may represent an important sentinel for climate-related changes coming in future decades to high Arctic areas. Southern and eastern Hudson Bay also are the 'downstream' point for most of the freshwater introduced into the Hudson Bay system. Within this region there is the opportunity to study subsystems within which coastal water masses are modified in winter by distant, large-scale river inflows from massive, regulated rivers (Nelson, La Grande), and compare them to those in which local natural river inflows (Great Whale) dominate the freshwater budget.

An additional issue motivating this research is that Inuit and Cree living in southeast Hudson Bay/James Bay make extensive use of the coastal corridor in winter, travelling on the landfast ice and harvesting fish and wildlife along the shores and in the flaw leads and polynyas. Harvested wildlife (e.g., seals, beluga whales, eiders) depend on the polynya and flaw lead network for winter refuges. The first impacts of changes in the functioning of the winter ice-ocean environment in this region will therefore be felt by Northern communities and the wildlife on which they depend. Indeed, concerns about possible changing sea ice and ocean conditions and their consequences here have already been raised (Gilchrist et al., 2006; Heath and Community of Sanikiluaq, 2011; NTK, 2008).

The overall goal of this project is to bring new scientific observations, integrated with the traditional knowledge of community research partners, to improve our understanding of the winter oceanographic conditions and interactions of river runoff, seawater upwelling and the sea ice cycle in modifying water masses and circulation in southeast Hudson Bay/ eastern James Bay.

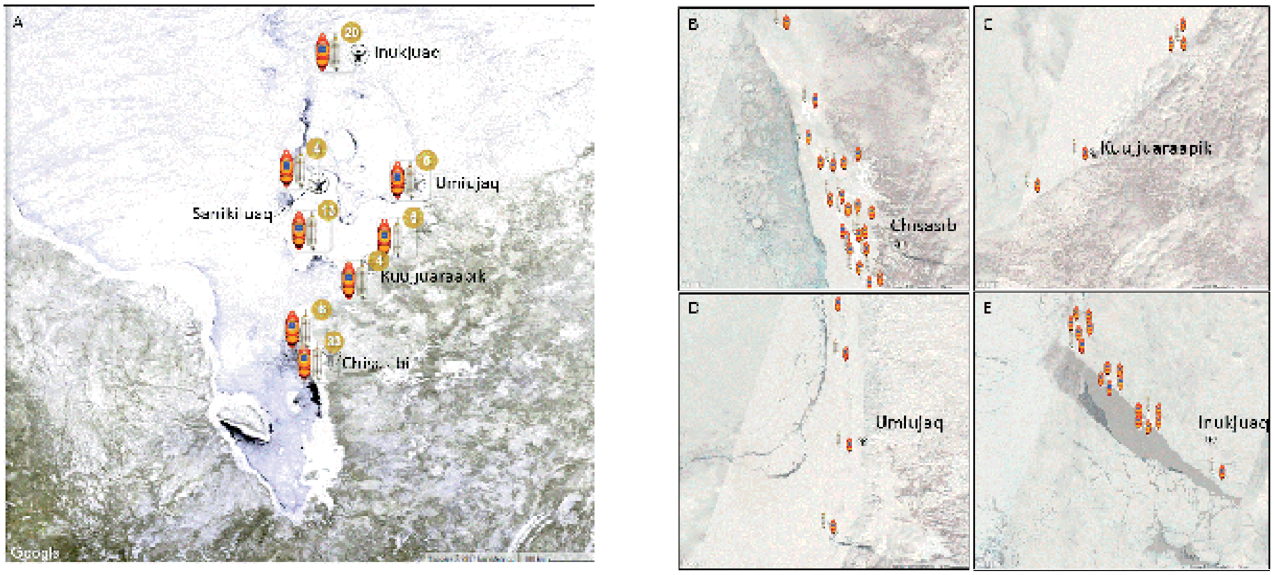

Figure 1. Maps showing distribution of winter sampling sites in southeast Hudson Bay and eastern James Bay in 2016. CTD casts are indicated by orange symbols. Images generated using Arctic Eider Society's IK-MAP platform.

Addressing these knowledge gaps are critical in order to have a basis from which to infer the probable effects of the hydroelectric and climate-related changes that are ongoing and also yet to come.

ACTIVITIES

Winter Field Work

Intensive winter field work was conducted in January-May 2017 in partnership with the communities of Chisasibi, Kuujjuaraapik, Umiujaq, Inukjuak and Sanikiluaq (Figure 1). In Sanikiluaq, winter 2016 marked a third year of quantitative observations of ice-ocean conditions, including conductivity-temperature-depth (CTD) profiles of the water column (bringing the total to ~63 total CTD casts), deployment of ice-tethered moorings equipped with CT sensors at three locations, and collection of water and ice samples. Between the winters of 2015 and 2016, Inuit research partners in Sanikiluaq worked a total of 141 person-days out on the ice as part of this project.

In Nunavik, 2016 was the second winter of working with community research partners in Inukjuaq, Umiujaq and Kuujjuaraapik to collect oceanographic data. We expanded the oceanographic program from ice measurements and CTD casts in 2015 to include seawater and ice core samples in 2016. A mooring equipped with a CT sensor to continuously monitor surface water salinity and temperature (2 m water depth) was deployed for the period of February 6 - April 6, 2016 at Duck Island, north of Kuujjuaraapik, an area widely used by hunters. Consultation meetings organized with local hunters, municipalities, landholding organizations and other groups at the beginning of the field campaign were highly successful and indicated broad support for continuing the project. To date, 78 CTD casts have been obtained along the coastal landfast ice platform around and between the three communities.

In Chisasibi, winter 2016 marked the beginning of a formal research partnership and additional funding for field work was contributed by the Cree Nation of Chisasibi. This community is very interested to learn more about the coastal oceanographic conditions in eastern James Bay because water properties such as

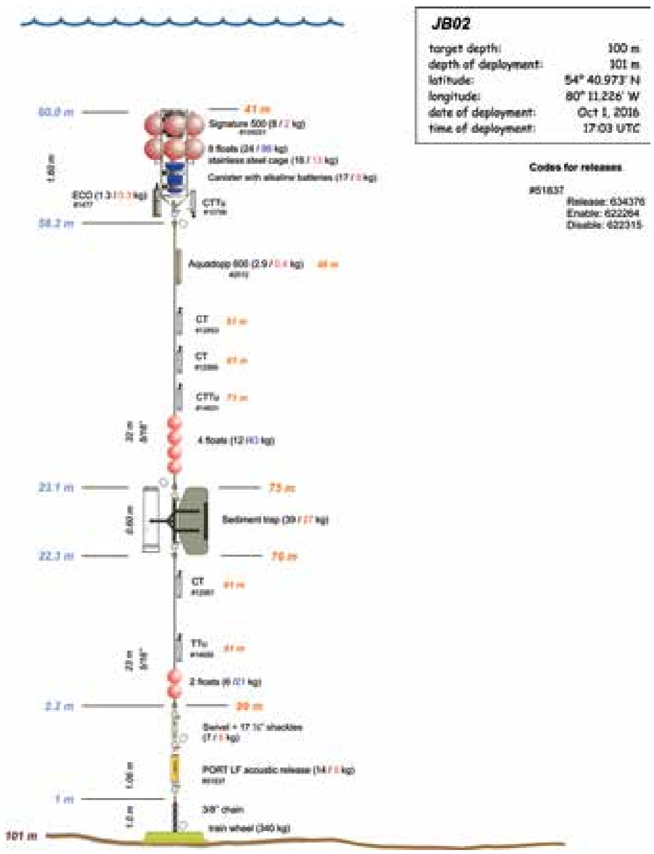

Figure 2. Mooring diagram for the mooring installed at the mouth of James Bay October 1, 2016, in partnership with the NSERC BaySys CRD project (D. Barber, Lead).

salinity, temperature, and turbidity can affect eelgrass ecosystems, which were once abundant north of Chisasibi (and now appear to be threatened). In January 2016, we deployed two large moorings near the mouth of the La Grande River Complex, equipped with instruments to measure current velocity profiles and a variety of water quality parameters. Turbidity, salinity and temperature were monitored up and down the coast through depth (CTD) profiling. A series of smaller CT sensors were installed under the ice at sites distributed northward from Chisasibi as far as Cape Jones/Long Island at the mouth of James Bay; these sensors logged salinity and temperature throughout the winter period. Water samples were collected in January and again in April/May, when moorings were recovered. Ice cores were recovered during the latter period.

Additional Field Work

In addition to the winter field work, open water oceanographic data were obtained in 2016 in partnership Sanikiluaq, the Nunavik communities, and Chisasibi. Sites around the Belcher Islands, along the southeast Hudson Bay coast, and in eastern James Bay north of Chisasibi were accessed by freighter canoe from the various communities. Data collected included CTD casts, water samples, and bathymetric information.

A third component of field work in 2016 was conducted in September-October from the CCGS *Des Groseilliers*. This work was accomplished through collaboration with the NSERC CRD project “BaySys”. Three personnel from this project were aboard in order to sample water and assist with installations of moorings. Five oceanographic moorings were deployed from September 26-October 3, 2016, including one in the study region at the mouth of James Bay (Figure 2). Sequential sediment traps were incorporated into the mooring design at three locations, including James Bay.

Sample Collection, Processing and Lab Analyses

In total, more than 150 water samples and 50 samples of snow and ice (representing subsections of 5-10 ice cores) were collected during winter field work in 2015 and a similar number in 2016. All water samples have been analyzed for salinity and oxygen isotopes ($\delta^{18}O$) and a subset for nutrients, chromophoric and fluorescent dissolved organic matter (CDOM and FDOM, respectively), and concentrations and isotope ratios of stable tracers including strontium (Sr). We are completing the analyses of salinity and $\delta^{18}O$ in the melted ice and snow samples.

Samples collected during the open-water season of 2016 are in the process of being analyzed. Water samples collected from aboard the CCGS *Des Groseilliers* are being analyzed for a large suite of parameters including those mentioned above as well as dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and alkalinity. These latter measurements will add to the novel tracer dataset useful for distinguishing various fresh water sources in Hudson Bay.

Water samples were collected in the field into amber HDPE bottles (insulated to prevent freezing) and transported back to the field lab in each community. Salinity and $\delta^{18}O$ samples were placed in glass bottles (rinsed three times) and then tightly capped and sealed with parafilm. Nutrients samples were filtered using precombusted glass-fiber filters (0.7 µm pore size, GF/F) and stored frozen (−20 °C). CDOM/FDOM and Sr samples were filtered using 0.2 µm pore size filters and refrigerated (4 °C) for 2–3 months until analysis.

Salinity was measured at Fisheries and Oceans Canada (Freshwater Institute and/or Institute of Ocean Sciences) using a Guideline Portasal (model 8410A). The machine was calibrated with 34.8 ppt OSIL standard seawater (salinity specific to batch) before and after each day of analysis. Oxygen isotope ratio of water ($\delta^{18}O$) in water and melted ice samples was determined using a Picarro Cavity Ring-Down Spectroscopy (model L2130-i) High Precision Isotopic Water Analyzer at the University of Manitoba. The precision of the instrument is 0.025‰ when measuring $\delta^{18}O$ in a freshwater sample. Each sample was analyzed six times in total, with only the last three measurements being used to obtain an average isotopic ratio. Samples were compared to the international V-SMOW standard. Water column samples were submitted to the laboratory of Dr. Jean-Éric Tremblay, Laval University, for nutrient analyses, and to the laboratory of Dr. Celine Guéguen, Trent University, for CDOM and FDOM and stable tracer (Ba, Sr, U) analyses. The absorbance of CDOM samples was measured from 250 to 700 nm using a Shimadzu ultraviolet visible UV 2550 dual beam spectrophotometer and a 10-cm rectangular quartz cell (Guéguen et al., 2011). A fluorescence spectrometer (Fluoromax 4, Horiba JobinYvon) was used to obtain the three-dimensional EEM spectra of the DOM samples with excitation wavelengths in the range of 250–500 nm in 5-nm intervals and with emission wavelengths ranging from 300 to 600 nm in 5-nm intervals. Data processing and QA/QC checks on physical oceanographic data sets (ADCPs, CTD and CTs) collected in 2016 are in the process of being completed.

RESULTS

Overview

We have now completed the second winter of observations of oceanographic conditions in southeast Hudson Bay working with community research partners in Sanikiluaq, Inukjuaq, Umiujaq, Kuujjuaraapik, and Chisasibi along the coast from the landfast sea ice platform. Through this collective effort, we have now generated the first significant wintertime ice/ocean data set for this region, including a large number of CTD casts, bottle (water) samples, ice samples, and mooring data. To address our project objectives, we have begun analyzing these data to determine:

a. freshwater distribution and inventories in space and time;
b. freshwater sources (river water vs. sea ice formation/melt);
c. inter-annual variability in ice and ocean conditions;
d. the utility of potential additional freshwater tracers; and
e. biogeochemical and biological implications of enhanced winter freshwater discharge.

The data collected in the Sanikiluaq area are in the most advanced stages of interpretation and dissemination. They were the focus of several presentations in 2016, together with earlier work. These Belcher Island data comprise parts of a Master's thesis project for Rosemary (Annie) Eastwood and a PhD thesis for Vladislav Petrusevich. Both students have completed their field work (data collection) and are in the process of completing their interpretations of the results and preparing manuscripts for publication in the peer-reviewed literature. The data collected along the southeast Hudson Bay coast and in eastern James Bay will comprise parts of a Master's thesis project for Samantha Huyghe, who started in September 2016, and a PhD thesis project for Chris Peck, who is starting in

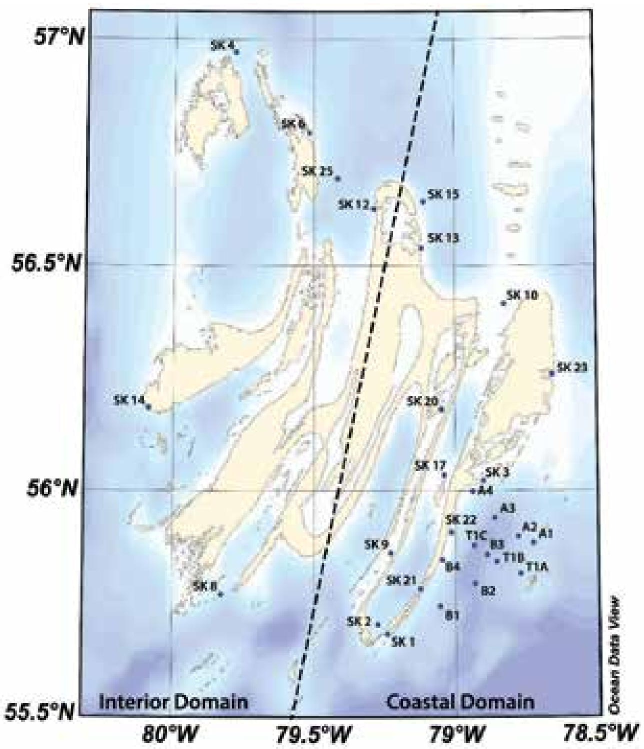

Figure 3. Map showing the Belcher Islands and sampling sites that we have accessed from the landfast sea ice platform. Oceanographic data distinguish two domains, the interior domain, north and west of the Belcher Islands and the coastal domain, south and east of the Islands.

May 2017. A Master's student who had begun working with the data in January 2016 had to depart the program for personal reasons. In addition to graduate students, undergraduate students both at University of Manitoba and Trent University have worked on smaller parts of the data set for specific projects.

Freshwater sources, distribution and inventories around the Belcher Islands

In summer, the coastal corridor in southeast Hudson Bay is the key transporter of freshwater from major source areas (rivers) in southern Hudson Bay and James Bay, northward to Hudson Strait. Borne by strong coastal currents, some freshwater from southern Hudson Bay reaches Hudson Strait by late fall/winter. It has been commonly assumed that very little freshwater remains in southeast Hudson Bay in winter. However, winter observations have been scarce.

Detailed study of freshwater distribution from the landfast ice platform surrounding the Belcher Islands shows two oceanographic domains in this area, differentiated by freshwater content and composition and by the structure of the water column (degree of stratification). To the north/west of the Belcher Islands (Figure 3), we find an 'interior domain': water masses with a uniform salinity of approximately 28-29 (Figure 4). In contrast, to the south/east of the Belcher Islands, we find a 'coastal domain', in which the winter water column is weakly stratified with relatively fresh surface waters (salinity 25-26) and low salinities extending down to depths of about 20-40 m (Figure 4). The presence of the fresher surface layer reflects 'upstream' freshwater sources and cyclonic circulation in Hudson Bay. The interior and coastal waters also differ in the nature of their deep waters; warmer and saltier water is preserved in a deep layer in the south due to the presence of salinity/density stratification that prevents vertical mixing. Time series for temperature and salinity recorded by a mooring at station SK1 during its deployment period from January 21st to March 18th 2014 show the presence of relatively fresh (S~26) surface waters in the first seven days of the deployment followed by an episode of surface under-ice warmer (and saltier) water, which might affect the thickness and formation of the land fast ice, then finally moderately freshened water (S~27-28) later in the period of record. The variations in surface salinity and temperature are interpreted in this case as being related to vertical mixing. Thus, detailed analyses of the controls on vertical mixing are underway.

In addition to river runoff, the seasonal addition of sea-ice melt represents an important source of freshwater to the Hudson Bay system. In southeast Hudson Bay, the seasonal input of river runoff has been estimated at 4-6 m and sea ice melt at 1-2 m (Granskog et al., 2011). On the other hand, it is expected that considerable brine is added to the surface waters in southeast Hudson Bay through the process of ice formation in winter. Our data, which include profiles of salinity and

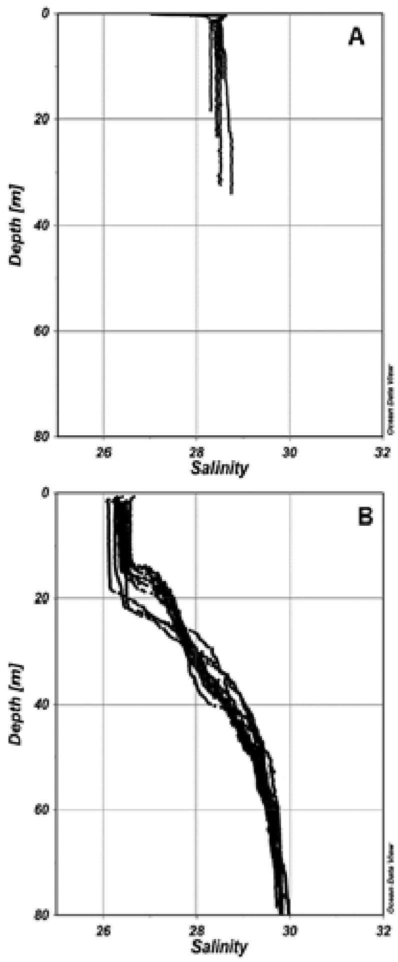

Figure 4. Salinity profiles in winter 2015 in the interior domain, north and west of the Belcher Islands (A), and the coastal corridor, southeast of the Belcher Islands (B). Locations of the sites are shown in Figure 3.

δ[18]O in the water column and the landfast ice, have been used to determine for the first time the relative contributions of river water and sea ice melt or brine in coastal waters surrounding the Belcher Islands in winter.

A biplot of salinity and δ[18]O (Figure 6) for water samples shows data generally distributed along a mixing line between low salinity, low δ[18]O values, reflecting the properties of river water, and high salinity, high δ[18]O values, reflecting the properties of seawater. The considerable degree of scatter around the mixing line

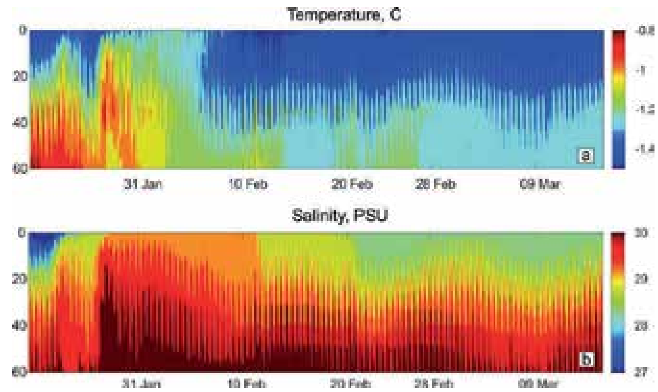

Figure 5. Temperature (a) and salinity (b) time series at mooring site SK 1 between a starting date of Jan 21st and end-date Mar 18 2014.

reflects the importance of freshwater additions by sea ice melt and freshwater withdrawals by sea ice formation. Quantitatively, the salinity and δ[18]O data indicate fairly large fractions of river water near the surface in the coastal domain (Figure 7), with evidence also of the brine cycle in the water due to sea ice melt in spring and sea-ice formation over winter. Specifically, we estimate that river water comprised ~23% of the surface waters (top 5 m) southeast of the Belcher Islands in January 2015 (Figure 7), which is more than twice as much as occurs in the interior domain at the same time period. In the preceding October (pre-freeze up), river water comprised ~13% of the upper water column (top 20 m) southeast of the Belcher Islands. Converting these fractional values into equivalent inventories (in units of metres) in the water column, the interior domain can be seen to have generally less than 1 m of river water equivalent in the winter time, compared to 2-4 m (depending on month and year) in the coastal corridor (Figure 8). River water increases from fall to winter and increases progressively through the winter in the coastal domain, while remaining at low and constant values in the interior domain.

The effect of ice formation/melt cycle is also evident in water column. In January, the net fraction of sea ice melt is approximately zero at most sites; a few sites still contained net sea ice melt (positive fractional values, Figure 7). Presumably this reflects residual from sea-

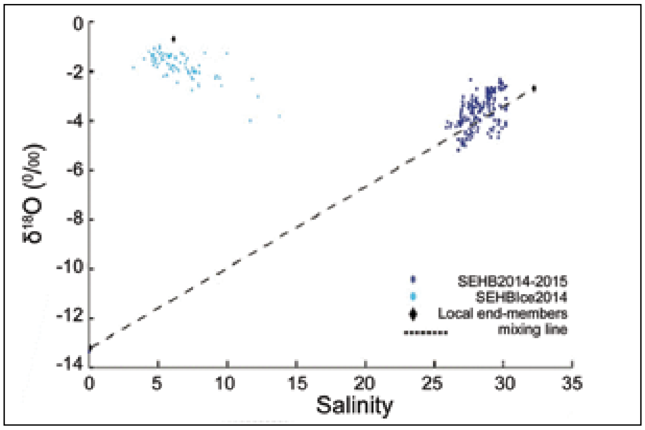

Figure 6. Plot of salinity vs. $\delta^{18}O$ in water and ice samples.

ice melted at the surface during the previous summer/fall, and that the cumulative sea ice formation in this region up to the point of sampling (mid-January) was insufficient to counteract the residual. There was about 50 cm of landfast ice in the area at the time of sampling.

Potential additional freshwater tracers

At least two "conservative" tracers (e.g., salinity and $\delta^{18}O$) are required to distinguish between river runoff

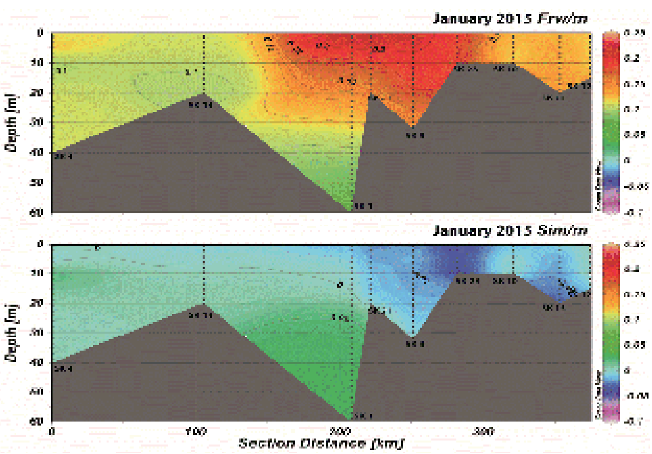

Figure 7. Fractions of river water (Frw) and sea ice melt (Fsim) throughout the water column along a section extending from north/west of the Belcher Islands (interior domain) to south/east of the Belcher Islands (coastal domain). Fractions were estimated using salinity and $\delta^{18}O$ data together and end-member values specific to southeast Hudson Bay.

and ice formation/melting in Hudson Bay. To further differentiate between fresh waters from different rivers (e.g., Nelson River/southwest Hudson Bay vs. La Grande Complex/James Bay), additional tracers are required. Thus, we are also collecting samples for dissolved nutrients, absorbing and fluorescing dissolved organic matter (CDOM and FDOM, respectively), and Sr concentrations and isotopes ($^{87/86}Sr$) to evaluate their potential as added tracers. Results are now available for a detailed study of the behavior of Sr in Hudson Bay estuaries (Gueguen et al., 2016), which showed both Sr and $^{87/86}Sr$ behaving conservatively in the Nelson and Great Whale River estuaries. This result provides promise for their use as tracers in southeast Hudson Bay.

The first data for CDOM and Sr isotopes for southeast Hudson Bay have recently been obtained. Around the Belcher Islands, CDOM concentrations in surface waters are found to be much higher in the coastal vs. the interior domain (Figure 9). The contrast similarly shows up for $^{87/86}Sr$ (Figure 10). High dissolved $^{87/86}Sr$ ratios are found in the top 3 m of the water column in the coastal domain sites, compared to low ratios throughout the water column in the interior domain. The isotope ratios in the interior domain surface samples can be described as marine-like, whereas those in the coastal domain show a greater influence of terrestrial inputs. Work is ongoing to confirm CDOM and FDOM signatures and $^{87/86}Sr$ ratios for the various rivers in the region and investigate any seasonal variation. The possibility of groundwater contributions to the freshwater budget in James Bay is also being considered. The possible influence of sea ice and its sediment load on altering surface water $^{87/86}Sr$ ratios is also under investigation.

Freshwater distribution in northeast James Bay/southeast Hudson Bay

First observations of the winter oceanographic conditions in northeast James Bay since regulation of the La Grande Complex show a large river plume extending northward from the river mouth at Chisasibi under the landfast ice in northeast James Bay (Figure 11). The plume strengthened throughout the winter, with freshening observed at all sites

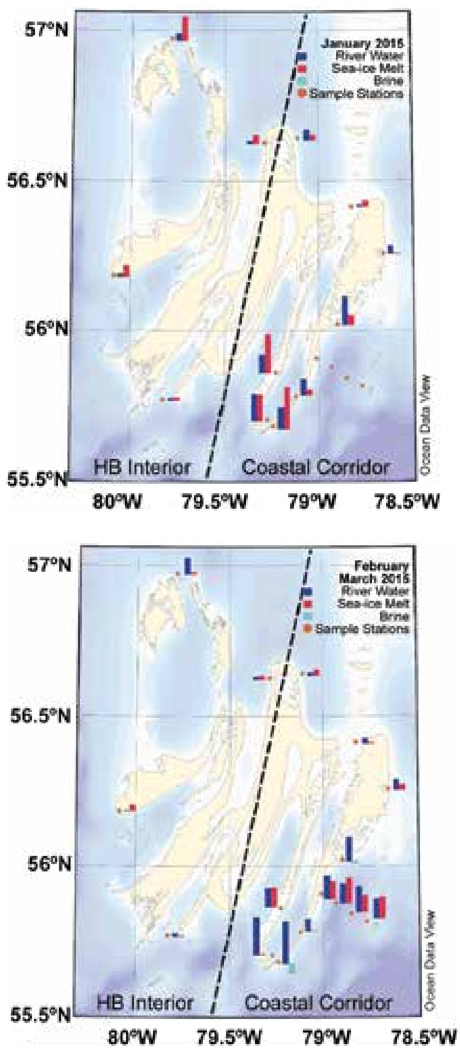

Figure 8. Map showing inventories of river water and sea ice melt (or brine) in the water column in winter 2015.

resampled between January and April 2016. At Cape Jones at the mouth of James Bay, CT mooring records indicate that surface salinity varied between 22 and 26 during January-April 2016 (Figure 12). Detailed analyses of the time series and forcing factors are underway.

DISCUSSION

The picture that is beginning to emerge about the winter oceanographic conditions in southeast Hudson

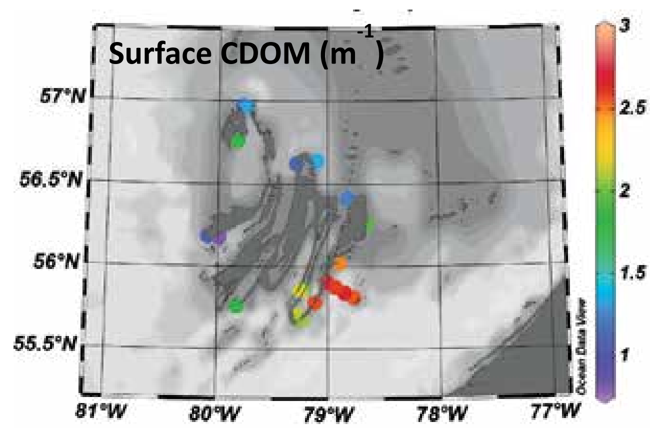

Figure 9. CDOM (a355), a tracer of river waters, in surface waters surrounding the Belcher Islands in winter.

Bay is one in which, within the coastal domain, a fresher surface layer is present throughout winter. This freshened surface layer results in salinity/density stratification that inhibits vertical mixing. Heat is preserved in deep water layers because of the stratification. The conditions in the coastal domain contrast strongly with conditions in the interior domain, which we were able to access from the landfast ice platform north and west of the Belcher Islands. In the interior domain, the water column shows no surface freshening. A uniform cold salty water mass extends down 40 m or more.

The salinity-$\delta^{18}O$ data clearly show that the source of the fresh water present in the surface layer of the coastal domain in winter is river water. At this point, novel tracers are not sufficiently developed for application in this region to confirm the specific river(s) of origin. However, the distribution clearly shows that river water is supplied to southeast Hudson Bay from upstream sources by the general cyclonic circulation in Hudson Bay. New data documenting the salinity of surface waters in northeast James Bay and the salinity of James Bay outflow (at Cape Jones) in winter 2016 imply that a possible (likely) source of river water to southeast Hudson Bay is the La Grande Complex. We are in the process of interpreting tracer data, which will help better describe the specific origin and transport of the freshwater.

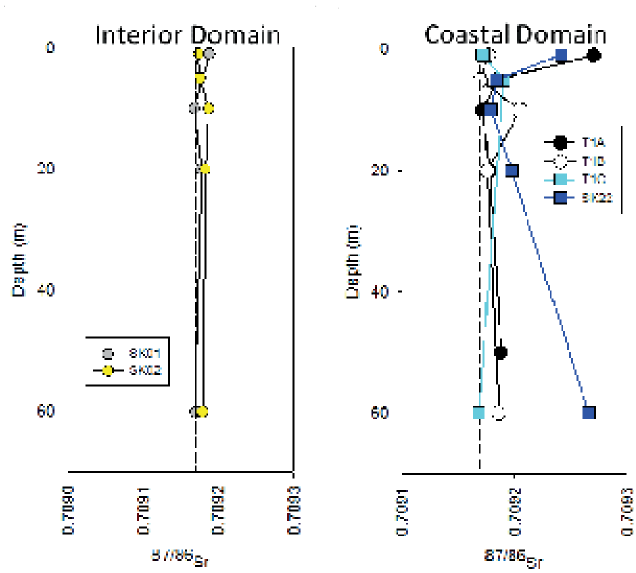

Figure 10. Dissolved $^{87/86}$Sr *profiles in the water column in the interior and coastal domains.*

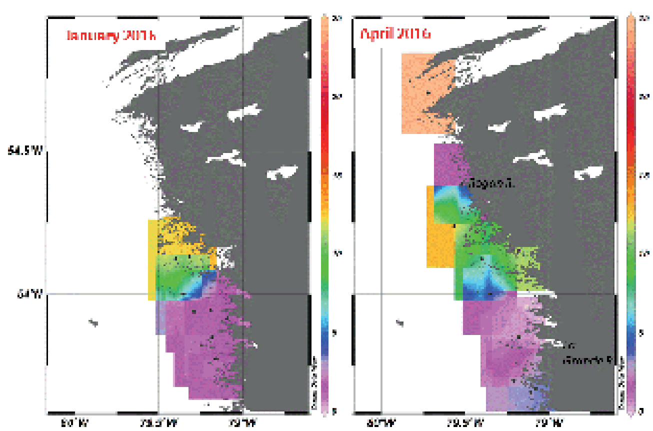

Figure 11. Surface salinity observed in northeast James Bay in January and April 2016.

In order to assess if and how freshwater distribution and sources have changed in the coastal corridor as a result of regulation of distant, large-scale rivers (Nelson, La Grande), one of the next tasks is a detailed comparison of pre- and post-regulation coastal oceanographic data. Some historical oceanographic data from the region have been obtained from the Marine Environmental Data Service and will be compared to the results obtained in winters 2014,

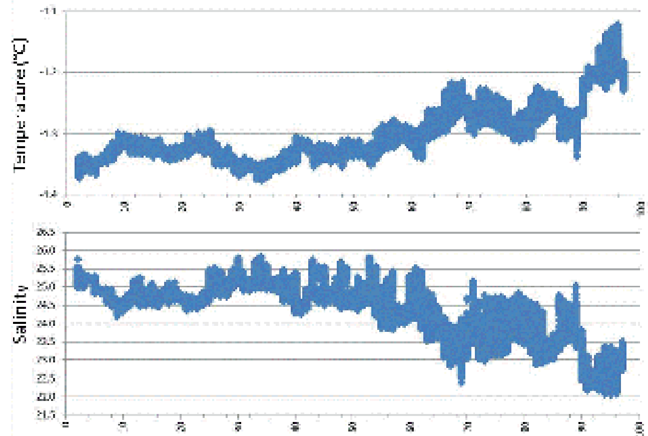

Figure 12. Time series of temperature and salinity at Cape Jones near the mouth of James Bay during a January-April 2016 deployment.

2015 and 2016. These two-plus years of data (the 2014 data set is small because it was a pilot study) provide an indication of interannual variability, which is important to consider in evaluating change.

The significance and physical, chemical, and biological implications of the freshened surface waters and stratification that we have now shown to be present in the southeast Hudson Bay coastal corridor in winter is also an area of ongoing work. The presence of freshwater in flaw leads or polynyas in winter can significantly impact the buoyancy forcing of these 'ice factories', with implications for ice formation and maintenance, deep water formation (which is needed to ventilate and renew the deepest waters in the Bay), and the depth of winter mixing. The depth of winter mixing is an important control on the degree of replenishment of nutrients from deep layers into surface layers and ultimately limits biological production the following year. Additional factors that influence the timing and extent of vertical mixing are tides and upwelling of deep waters due to atmospheric forcing (Dmitrenko et al., 2012). Internal waves in Arctic regions are also of scientific interest due to their role in vertical mixing and consequently their influence on heat budget and ice cover. In an ice-covered, stratified water column, with cold freshened surface waters overlying warmer saltier waters, the question of vertical mixing processes becomes of great importance because, put simply, if heat in deeper waters can be mixed upward then it will contribute to melting ice and/or prohibiting ice growth. Such processes are sometimes important for maintaining leads and polynyas. Preliminary interpretation of oscillations of temperature and salinity through the whole water column at the mooring southeast of the Belcher Islands is control by internal waves. Specifically, we believe internal tidal waves were produced from interaction of high tides typical for southeast Hudson Bay with the particular bathymetry of the narrow channel between the islands. This result highlight the importance of tides and bathymetry in vertical mixing processes in the coastal corridor of southeast Hudson Bay, and potential upward heat fluxes, with possible implications for polynya formation and maintenance in this region.

CONCLUSION

The Riverine Coastal Domain of the Arctic Ocean and adjacent seas such as Hudson Bay is believed to be uniquely sensitive to environmental change, particularly changes in the distribution of freshwater in winter (Macdonald, 2000). Freshwater discharges that occur in proximity to flaw leads or polynyas in winter can significantly impact the rate of ice formation and its properties, deep water formation, the depth of winter mixing, and hence the replenishment of nutrients from deep layers into surface layers and ultimately biological production the following year. Freshened surface layers in winter that produce stratification and inhibit vertical mixing also affect upward heat fluxes, with implications for the formation and maintenance of polynyas and flaw leads. Predicting the interactions of freshwater and other ice-ocean processes including vertical mixing associated with tides or upwelling of deep waters due to atmospheric forcing (cf., Dmitrenko et al., 2012) is, however, very complicated. Our two years of observations have collected data that, with careful analyses and interpretation, can help address some of these questions for southeast Hudson Bay.

The coastal corridor in southeast Hudson Bay is a priority region for understanding the interaction of freshwater and winter ice-ocean processes to modify water masses because it receives freshwater from rivers in southern Hudson Bay and James Bay, as well as sea ice melt. It is also an area of numerous polynyas and thus important in terms of sea ice formation and associated processes. We have made significant gains in quantifying the amount of freshwater remaining in the coastal corridor in winter and its general sources (river water). The next steps involve evaluating the evidence for whether the amount of river water in the coastal corridor in winter has increased in recent decades as the winter river discharges associated with hydroelectric regulation have increased dramatically (in some cases as much as ten-fold). Additionally, we are investigating the significance of the freshwater for physical, chemical and biological processes in the region.

This project is made possible by the excellent research partnerships we have established and continue to develop with Inuit and Cree from five communities in southeast Hudson Bay. The interactive mapping platform associated with the project (IK-MAP) facilitates the collaboration through straightforward and nearly real-time access to the field data. Ultimately, the results will be of interest to the scientific community engaged in studying environmental change in various Arctic areas as well as an important contribution to the ArcticNet Hudson Bay IRIS. They will also help inform decisions of Inuit and Cree managing the Nunuvut, Nunavik and Eeyou Marine Regions.

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MAPPING OF ARCTIC CANADA'S SEAFLOOR: CONTRIBUTIONS TO GLOBAL CHANGE SCIENCE, SUSTAINABLE RESOURCE DEVELOPMENT, SAFE NAVIGATION OF THE NORTHWEST PASSAGE, GEOHAZARDS AND ARCTIC SOVEREIGNTY

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ABSTRACT

This project undertakes the core seabed mapping component of the ArcticNet research program. Underwater acoustic mapping of the seabed relief, sediment distribution and shallow subsurface sediments are the prime datasets used by researchers to understand the geological processes shaping the seafloor, to assess geohazards and coastal habitats and to reconstruct the history of past climatic changes. These mapping results are applied to specific projects in this proposal including: *Marine geohazards to hydrocarbon development*: Canada has potentially huge economic benefits to gain by having access to the natural resources of the Arctic Archipelago region. Exploitation in this region however, can only proceed in a safe and responsible manner, by managing the potential detrimental impacts to the environment. A key requirement is to assess potential natural hazards that might result in harmful effects both to persons and the environment. Geohazards such as submarine landslides, collapse of offshore structures built on gas-bearing seafloor sediment and the impacts of glacial and sea ice must be known and their risk managed. *Opening new shipping lanes and improving navigational charting*: Despite previous focused mapping programs in the bottleneck regions, the Arctic Archipelago region remains sparsely mapped with shipping normally restricted to narrow singular corridors that may be ice covered. Because the CCGS *Amundsen* is operating a multipurpose mission throughout the region, there is a unique opportunity to simultaneously map uncharted regions to provide alternate pathways. *Past to present evolution of sea-ice regime*: Understanding past climatic history is key to accurately predicting potential future ramifications of a changing sea ice regime. To responsibly plan adaptation strategies, we need to be able to predict future climatic responses and their consequences. It is also the key to understanding the nature of these changes-i.e. are they part of a natural cycle or induced by present excess of greenhouse gases? The mapping is an essential precursor to designing seabed sampling strategies to recover undisturbed sediments.

KEY MESSAGES

The ArcticNet Seabed Mapping program directly addresses our knowledge gaps in three high priority areas:

- *Northern offshore oil and gas development*: One of the major impediments to safe and environmentally responsible oil and gas development in the Canadian Arctic Archipelago is the lack of knowledge about the presence of potentially unsafe natural seabed features (so called geohazards).
- *Seabed habitat related to living resources adjacent to communities*: While the national focus in on the benefits of the non-living resource extraction, at the community level, far more reliance is placed on the ability to develop marine living resources. A first step towards this is properly delineating the submerged seabed morphology and habitats in the vicinity of those communities.
- *The need for improved charting in the North*: To undertake the scale of marine shipping required to support non-living resource programs in the north, and to ensure access for the development of coastal living resources, the state of nautical charting has to be vastly improved. The ArcticNet mapping program now represents the most extensive source of modern high density bathymetric surveying in the Archipelago.
- *Better knowledge on short and long -term environmental changes*: Our work provides crucial geological information on the nature and morphology of the Arctic seafloor that allows us to reconstruct past stages of glacial advances and retreat, geohazards (earthquake and mass movements), sea level changes and land-to-sea sedimentary exchanges linked to permafrost degradation, relative sea level rise, etc.

OBJECTIVES

The exploration of the seabed to (1) study its geological history, geomorphology and sedimentary processes, (2) safely inventory its resources and habitats, and (3) establish navigable waterways all require increasingly precise and accurate mapping of the bathymetry, geophysical structure and sedimentary cover of the ocean bottom. In this perspective, the continental shelf and slopes of Arctic Canada are among the least understood on Earth despite burgeoning international interest in natural resources, shipping routes, environmental variability, and northern communities. While some areas of Arctic Canada have benefited from multiple high-resolution surveys (i.e., targeted areas of the Beaufort Sea), the vast majority of the channels within the archipelago as well as the adjoining continental shelf and slopes are characterized by a substantial knowledge gap. The bathymetry and seafloor geology of Arctic Canada are fundamental variables in the successful design and implementation of community, industry, and government policies regarding: (1) Arctic climate, (2) coastal and marine infrastructure, (3) sustainable development of sub-seafloor resources, (4) geohazards, (5) dynamics and resiliency of marine ecosystems, (6) safe marine navigation, (7) demarcation of national political boundaries, and (8) socio-economic and cultural change in northern communities. Such information is crucial to new and innovative research programs regarding biological and geological responses to climate change.

The objective of this project is to clarify the age and origin of Canada's Arctic seafloor using a multidisciplinary approach that contributes to the development of a robust geological and paleoenvironmental framework. Our specific objectives are to: (1) delimit past seafloor sedimentation patterns, including those associated with former ice sheets and ice shelves that inundated the Canadian Arctic; (2) document the modern sedimentary processes affecting the Arctic seafloor; (3) constrain previous and ongoing responses to and rates of relative sea level change; (4) generate long-term geological datasets of sea ice, oceanographic, hydrological and ecosystem variability; (5) systematically collect new regional geotechnical observations bearing on the engineering strength and slope stability of seafloor sediments; and (6) integrate knowledge of past depositional environments with regional geotechnical observations in order to develop an accurate model of regional seafloor stability, including the size, origin, timing, and environmental and economic significance of seafloor geohazards. In line with ArcticNet's Strategic Framework, the rationale of this project is to focus on better quantifying the spatial extent and risks associated with the seabed geological hazards that are so prevalent (iceberg/icekeel scouring, fluid and gas escape structures, mass wasting phenomena and seismicity hazards). As part of this, improved safety of navigation is an essential prerequisite to any natural resource exploitation. The CCGS *Amundsen* seabed mapping system remains Canada's best and most available asset capable of expanding safe shipping corridors in the Arctic Archipelago. She will provide our main contribution to hydrocarbon geohazards mapping in the Western Arctic.

KNOWLEDGE MOBILIZATION

- Active participation to Schools on Board during the Leg 3.
- More than 10 presentations in four scientific meetings.
- Participation to the IBCAO Workshop Surficial Geological Mapping of the Arctic held in Bremerhaven, Germany.
- Bathymetric data sharing agreement with the Canadian Hydrographic Service (CHS). The CHS will use our database to update their navigation chart in the Arctic. These data are crucial for a safe navigation throughout the Canadian Arctic Archipelago.
- Bathymetric data sharing with Memorial University of Newfoundland (R/V *Nuliajuk*).

- Collaboration on the GreenEdge project for MVP data, marine deployment of moorings, depth measurements.
- Delivery of bathymetric data to the Greenland government collected in their EEZ.
- Contribution of metadata to the Polar Data Catalogue.
- Data visualization and sharing via a web-based platform (GéoIndex+, U. Laval). These data are made available to ArcticNet scientists and on-demand to scientists from other groups or institutions.
- Publications of scientific papers in international peer-reviewed journals.

INTRODUCTION

This project implements underway geophysical mapping programs from the CCGS *Amundsen* in support of a wide variety of Network Investigators, parallel ArcticNet projects and external partner objectives. There is continual networking activity between the group that run the mapping and other ArcticNet NIs, collaborators and external partners to ascertain the needs of the specific science programs to see how they can best be met using the capability of the Amundsen mapping suites. Current foci for this program are the Beaufort Sea in the Western Arctic and the Eastern Baffin and Southeastern Ellesmere fjord systems in the Eastern Arctic.

The focus in the Beaufort Sea has been on identifying the presence, extent and risk associated with various seabed geological hazards ("geohazards"). The prime hazards of concern are ice keel scouring, expulsion of gas and fluid from the seabed, the potential for mass wasting (landslides) and the presence of buried shallow gas. Additional concerns are the geotechnical properties of the surficial (within 10 m of the seabed) sediments as this will affect the ability to construct infrastructure in support of drilling and oil field development.

In the Eastern Arctic, the 2016 mapping operations on the *Amundsen* have generated surveyed shipping corridors into previously completely uncharted fjords (e.g., Clyde Fjord, Trinity Fjord) and allowed to increase the mapping coverage in previously visited fjord systems (e.g., Buchan Gulf, Sam Ford Fjord, Scott Inlet). This activity is an essential precursor to safe scientific operations in the area. The Government of Nunavut is leading a Fisheries Resource assessment program in this area and this requires the establishment of safe navigation corridors and anchorages. The same data can then be used to assess seabed habitat in support of the same program.

The continual collection of underway swath bathymetric data over 14 years of opportunistic transits and site surveys by the CCGS *Amundsen* represents the single largest holding of high density, well navigated charting information in the Arctic Archipelago. The *Amundsen* actively uses this to safely meet her science objectives. That same data has been passed on to the Canadian Hydrographic Service to update their existing chart catalogue of the Archipelago region. A deliberate by-product of the mapping and science programs is the generation of highly qualified personnel in the fields of Arctic marine geomatics and marine geology.

ACTIVITIES

In the 2016 year, the following research activities involving the training of graduate students and postdoctoral fellows were performed:

Leg 1 – GreenEdge – Baffin Bay

All transits between stations were mapped with the multibeam sonar and the sub-bottom profiler. The hydrographers onboard also acquired 10 MVP transects (total of 575 casts) across Baffin Bay, from Greenland to Baffin Island. P. Lajeunesse and his team have provided an important support during these operations, especially by providing bathymetry and water column imaging.

Leg 2 – ArcticNet-NetCare - Baffin Bay, Nares Strait, Kayne Basin and Northwest Passage

Additionally to the usual transit mapping, other research activities were performed: (1) collaboration on sediment coring in Frobisher Bay (T. Bell, D. Forbes, Geological survey of Canada), (2) coring at five sites for postglacial history reconstruction and fjord sedimentation processes analysis (P. Lajeunesse, G. St-Onge), (3) four MVP transects in Nares Strait and Kane Basin (ArcticNet) and (3) assistance of mooring deployment in Queen Maud Gulf (Weston Foundation-ArcticNet). More than 120 hours of dedicated mapping was performed in multiple environments: (1) ROV dive sites for habitat identification and classification (C. Nozais, E. Edinger, P. Archambault), (2) navigation routes (Canadian Hydrographic Service – CHS) and sediment coring sites within Frobisher Bay (E. Edinger, T. Bell), (3) glacier retreat and moraine mapping in Trinity Fjord (L. Copland, P. Lajeunesse), (4) geomorphology and stratigraphy of Baffin Island fjords (P. Lajeunesse), (5) increasing bathymetry coverage in Queen Maud Gulf (CHS-Weston Foundation) and (6) iceberg scouring sites East of Devon Island and Qikiktarjuuaq ice island keel mapping (D. Mueller).

Leg 3 – ArcticNet - Beaufort Sea, Northwest Passage, Baffin Bay and Labrador Sea

As for Leg 2, the 2016 Leg 3 research activities included four MVP transects in Amundsen Gulf mooring deployments and recoveries (ArcticNet), coring sites mapping in Beaufort Sea, M'Clure Strait and Baffin Bay (GSC, J.-C. Montero-Serrano, A. Pienkowski, T. Lakeman), increasing the multibeam bathymetry coverage in Pond Inlet Trough, Broughton Trough and Clyde Inlet for the geomorphology of fjords (P. Lajeunesse) and a re-survey of the Qikiktarjuuaq ice island (D. Mueller).

Grand Lake (Labrador) Mapping Project

In this project, P. Lajeunesse is responsible for collecting high resolution bathymetric and acoustic stratigraphy data in one of the deepest lakes of northeastern North America. This project is undertaken with scientists of the GSC, UQAM, INRS and Ouranos with the collaboration of Hydro-Québec and Manitoba-Hydro. During our operations in 2016, we have been in close contact with the community of North-West River (Labrador). We also hired a local guide from the community to assist us during this survey.

RESULTS

CCGS Amundsen Mapping Program

The 2016 season allowed mapping new sectors of Baffin Bay (including offshore Greenland), Baffin fjords, Nares Strait, Labrador and Beaufort seas (see Figure 1). The Laboratoire de géosciences marines (U. Laval) performed all the transit and dedicated mapping activities. These data will allow understanding the glaciology of past ice sheet and their links with climatic events and geohazards. The newly acquired data has been requested by more than 10 users in 2016 and is currently being used by graduate students for their theses.

Geology

The legacy and new datasets collected by our team, including the multibeam bathymetric and accompanying subbottom profiler data have been fundamental in discovery and further directing of science in a number of fields. Some recent examples from the network of researcher follow.

The increase in sonar seabed coverage in the northern Banks Island Shelf and M'Clure Strait region across the past three field seasons has enabled a vast improvement in understanding of the mainly glacial, system. Surficial and shallow subsurface geology map production/interpretation has begun in the Kugluktuk to Amundsen Gulf area. The 2014 sonar data enabled identification of several potential coring sites that were successfully visited by NRCan and its ISMER, MacEwan U. and NGU collaborators in 2016. Piston cores are the first to be taken and will contribute in the next few years to glacial and post glacial reconstruction and geohazard assessment. Analysis begins Feb. 2017. 2016 box core push core samples are presently being analysed for Pb-derived sedimentation rates towards a Holocene framework and age-dating the most recent mega-slides (U. Manitoba collaboration, Douglas Murray, Zou Zou Kuzyk). A Holocene and late glacial chrono-seimostratigraphic framework (based on ArcticNet cores and seismic) has developed far enough to be applied to several phenomena, including mass-transport deposits (Marine Geology in review), oceanographic current evolution (King et al. 2016, 2017), mud volcano initialization, and pingo rates of change.

Main scientific results published in 2016 include a better understanding of flood layers related to important discharge events at the Nelson River mouth (Quentin et al., 2016). Our work illustrated the influence of dams on the sediment dynamics and that longer sediment cores could be used to reconstruct the frequency of major floods during the last millennia. Studies have been undertaken on the mineralogical, geochemical, magnetic, and siliciclastic grain-size signatures of surface sediments from the Mackenzie-Beaufort Sea Slope and Amundsen Gulf, in order to better document the redox status, detrital particle provenance, and sediment dynamics in the western Canadian Arctic. Throughout this research, NIs and their students (A. Gamboa, C-E. Deschamps, P-A. Desiage, O. Kutos) were able to document that: (1) western Canadian Arctic may be divided into four provinces with distinct sedimentary compositions (Mackenzie Trough-Canadian Beaufort Shelf; southwestern Banks Island; central Amundsen Gulf; and mud volcanoes), (2) more turbulent mixing conditions and thus a well-oxygenated water column prevailing within the Amundsen Gulf compared to Mackenzie Trough and Canadian Beaufort Shelf, (3) the present-day sedimentary dynamics on the Canadian Beaufort Shelf is mainly controlled by sediment supply from the Mackenzie River, (4) deposition of coarse magnetic grains in the deglacial interval from the Beaufort and Chukchi margins was controlled by high IRD inputs from the Laurentide Ice Sheet, and (5) by using variations in the Earth's magnetic field (inclination, declination and relative paleointensity), a chronology for sediments of the western Arctic Ocean has been established since the last deglaciation. These results provide a baseline to better interpret, in terms of sediment dynamics and climate change, the mineralogical, magnetic and geochemical signatures preserved in the southern Beaufort Sea sedimentary records, which may then help to place current western Arctic climate change (Gamboa et al., 2017).

All the above are significant and will spawn further investigation to be incorporated into future publications.

On-line Multibeam Data Management

The UNB-based multibeam bathymetry data processing and on-line distribution model continued to be in service in 2016 (http://www.omg.unb.ca/Projects/Arctic/google/), but new *Amundsen* data from the 2014 to 2016 seasons were only accessible on request due to the development of a new distribution platform at U. Laval. The newly acquired data are yearly integrated with the OMG database from previous years and available online on a webportal (Geoindex+; U. Laval, see Figure 2). Moreover, our team started working on building a GoogleEarth-based platform for visualization and analysis of 2003-2016 of subbottom acoustic profiler data (see Figure 3).

Updating the database on a yearly basis to a geodatabase system will allow a full suite of supporting data and interpretation for future research application and publishing.

Incorporation of Amundsen data into CHS Nautical Charts

The mapping data, generated by the *Amundsen,* is delivered to the Central and Arctic region of the

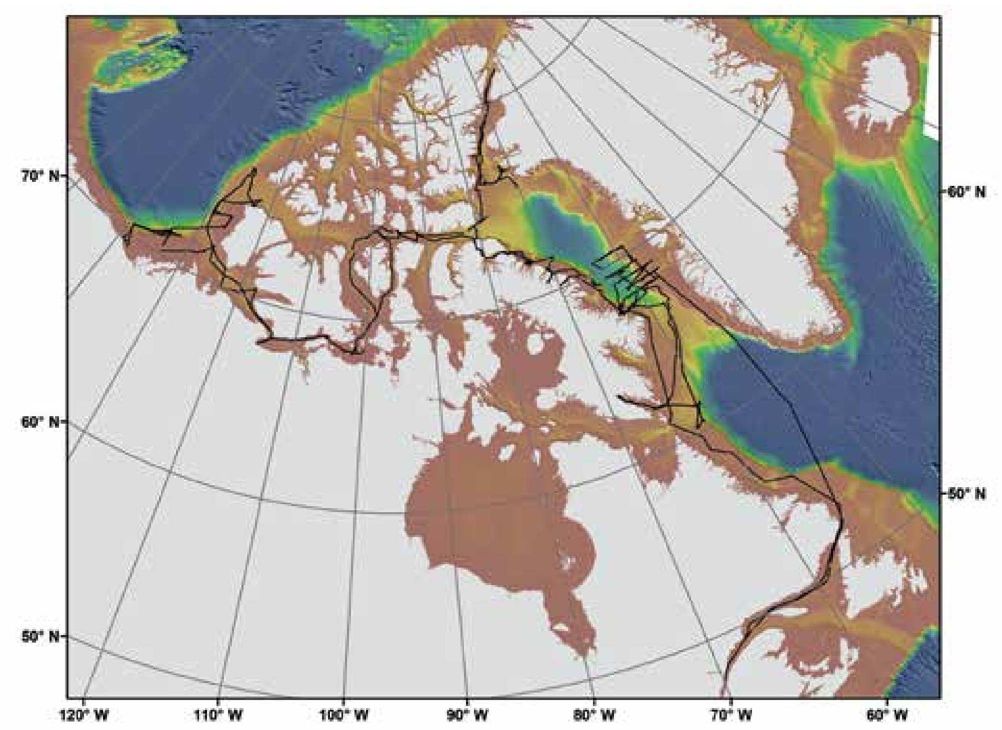

Figure 1. New mapped sectors of Baffin Bay (including offshore Greenland), Baffin fjords, Nares Strait, Labrador and Beaufort seas.

Canadian Hydrographic Service annually. These data are continually used implement and update their charting products.

DISCUSSION

Since 2014, this role was passed on to Patrick Lajeunesse at U. Laval. *Amundsen* mapping logistics, operations, processing and dissemination has been managed by his laboratory involving Gabriel Joyal (Research Staff), Etienne Brouard (PhD student), Annie-Pier Trottier (PhD student), Charles de Grandpré (PhD student) and Jean-Guy Nistad (U. Hamburg). His group also provide support for delivering multibeam bathymetry and subbottom profiler data to other NIs of this project and from other ArcticNet projects. These data are crucial for selecting coring sites. Water column data recorded by the multibeam echosounder is also particularly important during the recovery of moorings.

Dealing with Data Ownership Issues: Current Distribution Model: One of the greatest benefits of the ArcticNet Seabed Mapping Project over the past decade has been the open distribution of the growing seabed mapping database. Through an internet portal, the global scientific community has been able to browse the data for the entire Archipelago at resolutions as fine as 10 m. Our greatest scientific insights into the seabed processes have come about from open availability of the serendipitous collection of transit data. To get always freely given out. The data on this website did not include the data of the 2014, 2015 and 2016 because of the transfer of the leadership of the project from John Hughes Clarke (UNB) to Patrick Lajeunesse (U. Laval). The new portal has been effective since March 2016 and is hosted on the GeoIndex+ portal (http://geoindex-plus.bibl.ulaval.

ca/) of the Centre GéoStat and Library of Université Laval (see Figure 3). In 2016, we received four direct data request from scientists and organisations across the country. Many of them requested (and received) bulk downloads of the entire Archipelago dataset. At the beginning of 2017, we transferred all the multibeam echosounder and positioning data to the Canadian Hydrographic Service. These data will implement navigations charts in the Canadian Arctic. Since the *Amundsen* sailed in Greenland waters in 2016, the bathymetric data acquired in this territory have been made available to the Greenland Government to increase their database (see CCIN). Historic handling of Third Party Directed Mapping: The 2009-2011 oil and gas partnership programs involved the largest financial contributions to date to ensure focused mapping (and other) programs in the Beaufort Sea. As a result, for the first time, the issue of data access was raised. It is important to emphasize that this was a partnership, not a contract. Unlike commercial contractual arrangements, just a two-year delay in the posting of those datasets was agreed upon. Within that time frame, ArcticNet NIs and federal agencies (NRCan-GSC, CHS) did have full access to the data. At the conclusion of the 24-month delay, however, the data went up in exactly the same free manner as all the rest.

Our research work has allowed us to train dozens of students with the participations of highly qualified research professionals. These projects have provided important information of the nature and timing of environmental changes and events recorded in the seafloor sediments. Many of the datasets generated during this project provide a baseline database that will be used in the future to monitor and trace these environmental changes on a short-term basis.

CONCLUSION

The interest in seabed morphology extends from the shallow water need for safety of navigation to

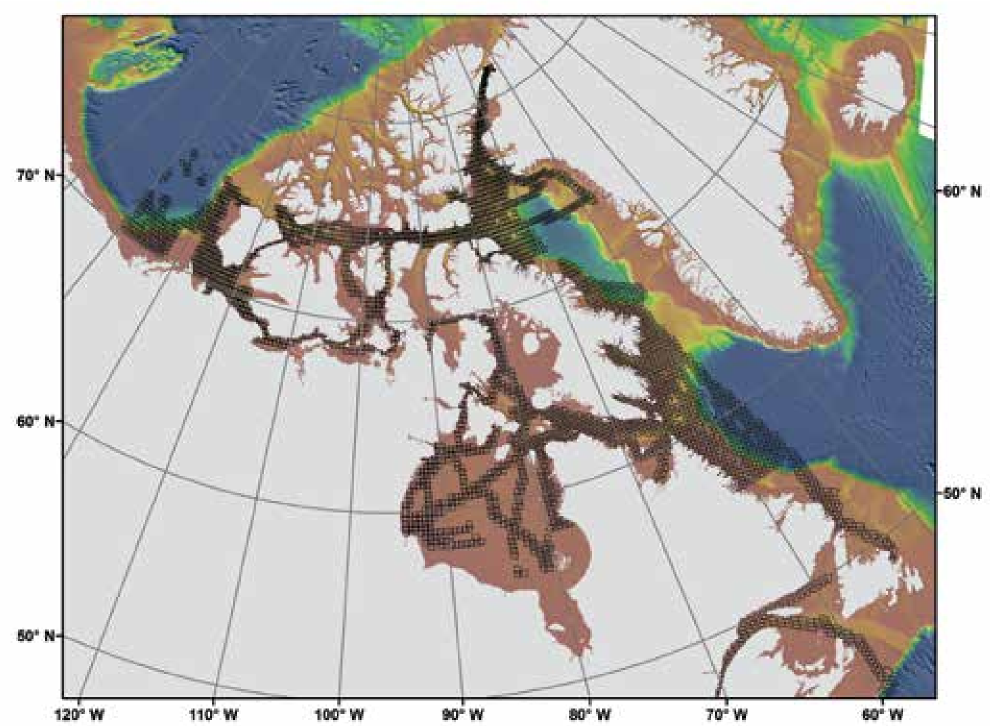

Figure 2. The newly acquired data are yearly integrated with the OMG database from previous years and available online.

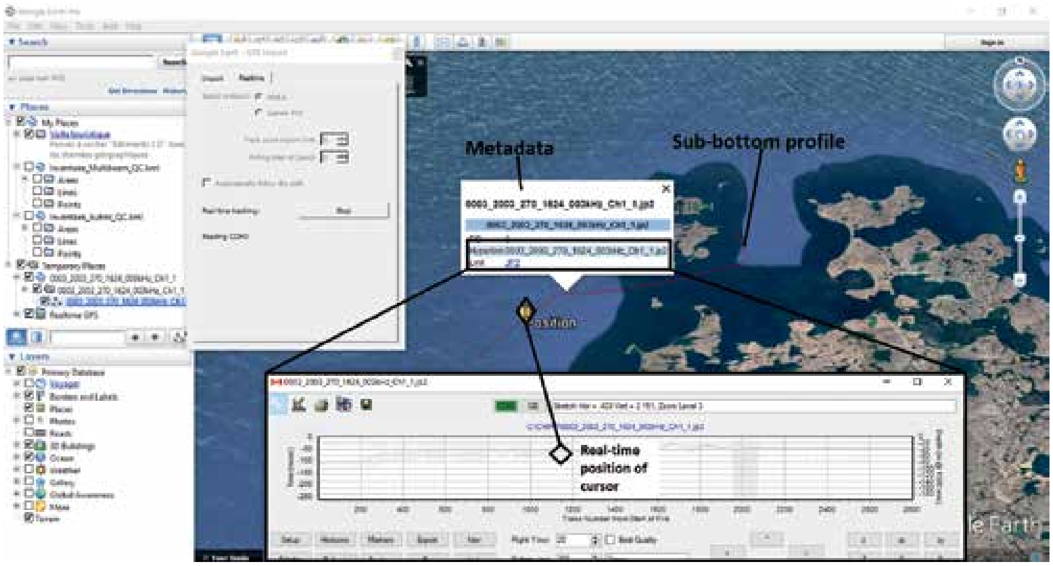

Figure 3. GoogleEarth-based platform for visualization and analysis of 2003-2016 of subbottom acoustic profiler data.

the deeper margin wherein Canada's greatest future hydrocarbon prospects lie.

Current highlights are threefold and include:

- Improved understanding of the glacial history and geohazards potential of the Western and Eastern Arctic regions to promote responsible non-living resource exploitation;
- Document the history of long- and short- term environmental changes recorded in the sediments and the seafloor morphology of the Arctic marine waters of Canada;
- Building a framework of bathymetric and habitat databases in the eastern Canadian Arctic to facilitate future community marine living resource exploitation; and
- Acquiring baseline bathymetric data in uncharted waters to update the nautical charting coverage, thereby improving safety of navigation across the entire Arctic Archipelago.

All of these serve the underlying mandate of ArcticNet to study the impacts of climate change and modernization in the coastal Canadian Arctic. The mapping program is precisely the "development and dissemination of the knowledge needed to formulate adaptation strategies and national policies".

While the four highlights are our current foci, the greatest success of the program over the past decade has been the growth and open distribution of underlying knowledge about the seabed across the Canadian Arctic Archipelago and the diffusion of this new data to governmental agencies, scientists, communities and the private industry.

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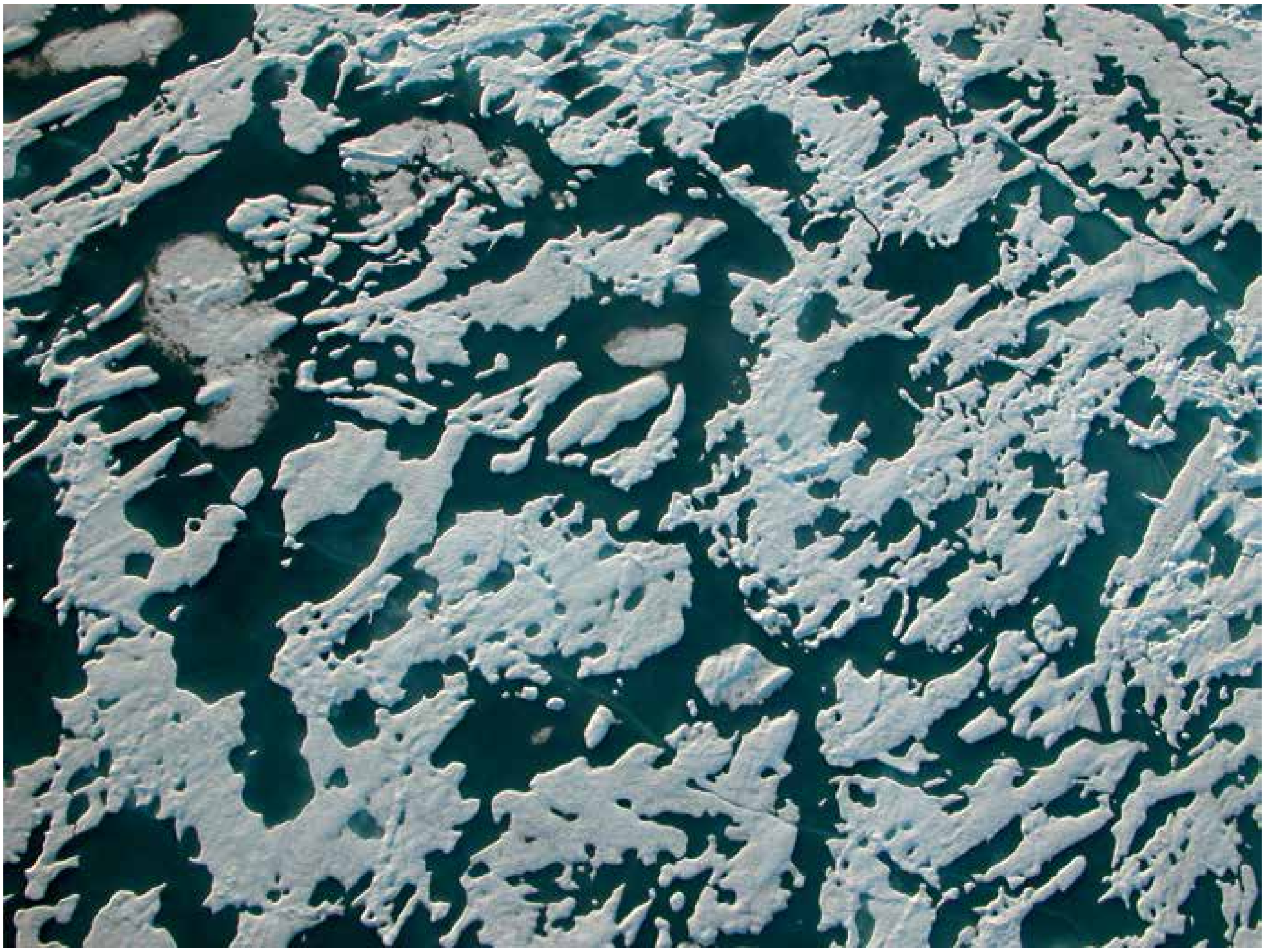

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MARINE BIOGEOCHEMISTRY AND SURFACE EXCHANGE OF CLIMATE ACTIVE GASES IN A CHANGING ARCTIC SYSTEM

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ABSTRACT

Oceans play an important role in cycling gases that interact with the Earth's atmosphere and climate system. Many of these gases (CO_2, CH_4, N_2O) contribute to climate warming, while others (DMS) have a cooling effect by promoting cloud formation. The Arctic Ocean is thought to be particularly active in exchanging these gases, but putting precise numbers on that exchange is challenging, due largely to the complicating presence of sea ice. As an additional complication, the sea ice cover is changing dramatically in response to climate change, which in turn is modifying how gases are cycled. The overarching goal of this project is to understand the present role of the Arctic Ocean in gas exchange, and identify feedbacks and linkages to climate change. To achieve this goal, we will work primarily from the CCGS *Amundsen*, measuring CO_2, CH_4, N_2O, and DMS in the atmosphere, sea ice, and seawater. We will also make measurements to investigate the biological, geological, and chemical (biogeochemical) processes that produce and consume these gases, and the processes that allow gases to transfer between the ocean and the atmosphere. These measurements will feed into numerical models to predict the future role of the Arctic Ocean in gas exchange. Our work on understanding CO_2 exchange will help us monitor and predict ocean acidification – an emerging problem in the Canadian coastal Arctic. The project will contribute to ArcticNet's IRIS assessments by quantifying the potential impacts of ocean acidification, and by better understanding important biogeochemical cycles. Our research will complement many other ArcticNet projects, including those studying sea ice, contaminant cycles, and marine food webs. Perhaps most importantly, the project will train a large cohort of highly qualified personnel, who will enter the workforce prepared to help Canada adapt to a changing Arctic.

KEY MESSAGES

Our project integrates four highly-coupled themes: carbon chemistry (including air-sea exchange, ocean acidification and the changing stores and distribution of inorganic carbon), climatically active trace gases (including carbon dioxide - CO_2, methane - CH_4, nitrous oxide - N_2O, and dimethyl sulfide – DMS, in association with biogeochemical drivers supporting outgas and uptake in the marine system), and modeling, to understand how the relationships among gas exchange dynamics and biogeochemical processes that determine the geochemical make up of the seawater vary over large spatial and temporal scales. In this past year, the key messages associated with each theme include:

Carbon chemistry

- Sea-ice melt is generating a thin layer of aragonite-undersaturated[1] waters in the Canada Basin.
- The intrusion and upwelling of CO_2-rich Pacific waters in the eastern Beaufort Sea and the western Canadian Arctic Archipelago brings aragonite-undersaturated waters within 50 meters of the surface.
- The intrusion of pre-acidified Atlantic waters (from uptake of anthropogenic CO_2 in the North Atlantic) at mid-depths in basins of the Arctic Ocean is eroding the aragonite saturation horizon from below (i.e., the aragonite saturation depth is getting shallower).
- The timing and magnitude of freshwater inputs (sea ice melt and river inflow) plays an important role in carbon biogeochemistry and acidification in Hudson Bay in that distributions of alkalinity (TA), dissolved inorganic carbon (DIC) and aragonite saturation Ω_{AR} generally follows salinity.
- Surface values in Ω_{AR} in Hudson Bay remain above 1 (saturated), but the depth of aragonite-undersaturation shoals to within 25 m of the surface in south-eastern Hudson Bay.

[1]*Aragonite is a calcium carbonate mineral. Its saturation state (Ω_{ar}) is often used to track ocean acidification. In general, if Ω_{ar} is greater than 1, the mineral is stable, but if Ω_{ar} is less than 1, the mineral is vulnerable to dissolution (AMAP, 2013).*

- Seawater in the southern Kitikmeot Region (Dease Strait, Queen Maud gulf) is supersaturated in pCO_2[2] during late summer, suggesting an extensive region of CO_2 outgassing.

Climatically Active Trace Gases

- Surface water concentrations of DMS[3] show significant hot-spots in regions of hydrographic frontal zones and localized sea-ice melt.
- Observation of strong near-surface DMS gradients across hydrographic fronts associated with sea-ice dynamics and salinity-driven density features.
- DMS production in melt ponds is significant and could be as high as in open waters (up to 12 nmol L^{-1}).
- Distinctive and positive DMS gradients (ca. one order of magnitude) are observed from open waters towards oceanic inlets and fjords of the Canadian Arctic Archipelago.
- Ice-edge blooms are confirmed as important reservoirs of DMS (up to 60 nmol L^{-1}).
- Under-ice concentrations of DMS are shown to be as high as ice-edge pools showing the inherent potential of these sources for air-sea exchange particularly during ice break-up and lead opening.
- Sea-ice processes exert a strong influence on polar microbial communities and their production of DMS.
- The ArcticNet domain is a weak source of methane to the atmosphere.
- Photoproduction of methane from dissolved organic matter is observed in water samples collected from Labrador Sea, Baffin Bay, Mackenzie Shelf, and Canada Basin.
- Strong sources of CH_4 and N_2O were observed over the Bering and Chuckchi Shelf regions. Stable isotope analysis of CH_4 reveals that oxidation is a primary removal mechanism.

Modeling (main lines of progress)

- The implementation and coupling of a sea ice algae ecosystem and a pelagic ecosystem has been completed. The two systems are linked by the exchange of nutrients (mainly through diffusive flushing into the ice, and detrital release from the ice).
- Biogeochemical carbon and sulfur cycles have also been implemented in the 1-D model. The model is refined through access to the group's field measurements of the ecosystem dynamics, including carbon and sulfur cycles associated with DIC (Dissolved Inorganic Carbon), DMS (Dimethyl Sulfide) observed near Resolute, Nunavut. Parameter sensitivity analyses and modeled-observed data comparisons were focused on the critical time period during spring thaw.
- The 1-D model sensitivity studies served as a foundation for implementing biogeochemically active tracers in a larger 3-D ocean-ice coupled model for the marine Arctic, which is now in progress. When implemented, the model will be able to make predictions of the large-scale air-sea exchange of two climatically active gases (DMS and CO_2) in the marine Arctic, during both present and future climate scenarios.

OBJECTIVES

This project's overarching goals remain unchanged and are:

1. To assess climate-active gas transfer and ocean acidification in the Canadian coastal Arctic, and monitor potential climate change-effects on trace gas cycling;
2. To elucidate the underlying processes controlling the transfer of climate-active gases and ocean acidification;

[2] *A measure of dissolved concentration of CO_2 in the seawater.*
[3] *Dimethylsulfide is a biogenic gas linked to aerosol projection in the atmosphere.*

3. To represent the marine Arctic ecosystem through a coupled physical and biogeochemical model and, in particular to improve the representation of mechanisms that are important to the air-sea exchange of carbon and sulfur in the seasonal ice covered areas of the Arctic Ocean; and
4. To forecast future gas exchange and ocean acidification, and to identify feedbacks to global climate change.

Research this past year related to field, lab and modeling activities, and data synthesis in support of project objectives. Goals included:

- To document variability in the carbonate system of seawater in the waterways and bays of the ArcticNet domain, and to determine the main processes that underpin variability using data sets associated with the team extending from current projects to those pre-dating 2003;
- To characterize implications of variability in carbonate system parameters on regional atmospheric CO_2 budgets and ocean acidification;
- To quantify the relative contribution of freshwater inputs (river, sea-ice melt, snow and glacier melt) and oceanic water masses (Pacific, Atlantic) to the vertical structure of the water column and the transfer of heat, salt and carbon between the North Pacific and North Atlantic through the Canadian Arctic Archipelago and into Baffin Bay;
- Conduct a case study focusing on the potential air-sea exchange of CO_2 in the under-studied southern Kitikmeot Region, and collect samples for baseline assessment of ocean acidification state;
- To determine the spatial distribution of DMS, CH_4 and N_2O in the waterways and bays of the ArcticNet domain;
- To quantify the relationships between sea-ice formation and carbon transport processes in laboratory experiments;
- To develop protocols for validating and calibrating in-situ CO_2 system sensors for deployments in polar waters;
- Develop parameterizations of key biogeochemical processes in sea ice (ice algae growth, carbon and DMS fluxes at sea ice interfaces);
- Through parameter sensitivity analyses in the 1-D model, identify key observables that need further study in order to better constrain the model output, i.e., which parameters (and associated physical processes/observables) affect the model output more strongly, and which affect the output less so; and
- Implement derived parameterizations into a 3-D model framework, to assess carbon and DMS budgets and determine the effect of sea-ice biogeochemical processes in present and future climate scenarios.

KNOWLEDGE MOBILIZATION

Data are being shared among programme participants through university server data archives, as well as dedicated workshops and network annual science meetings. This has led to joint publications (nine published and six submitted in the reporting year), student co-supervisions as well as the validation of numerical and their parameterization. In addition, exchange of data, as well as access to analytical and computational facilities, have allowed university researchers to complement their database and DFO researchers to fulfill some of the DFO mandates in Arctic regions. Additionally, research informs the science community through peer-reviewed publications and presentations at national and international conferences. For example, our work supports Arctic marine ecosystem model development as part of the Aquatic Climate Change Adaptation Services Program (ACCASP) at IOS (Fisheries and Oceans Canada and CCCma (Canadian Center of Climate Modelling and Analysis) as well as activities within the Arctic Monitoring and Assessment program (AMAP) for Arctic Ocean Acidification.

Other specific examples of knowledge 'traction' or mobilization include:

- Miller et al., 2015, is serving as a primary methodological reference for studies of sea-ice biogeochemistry, as evidenced by a healthy Google Scholar citation rate.
- Recovered Arctic carbon time series dataset (Giesbrecht et al., 2014) has been incorporated into the GLODAP-2 global ocean carbon data product.
- AMAP Assessment 2013: Arctic Ocean Acidification drew substantially on data and knowledge generated during this project.
- Insights developed by this project directly contributed to the new science plan of the Surface Ocean-Lower Atmosphere Study (SOLAS).
- New model parameterizations are available for the science community (paper - Mortenson et al. submitted), including modeled assessments of impact of sea ice biogeochemistry on carbon and DMS fluxes in the Arctic (Mortenson et al., in preparation, Hayashida et al. , in review – in collaboration with the CCAR NETCARE project).

INTRODUCTION

The Earth's oceans play an important role in global cycles of climate-active gases. For example the "ocean carbon sink," absorbs roughly one-quarter of anthropogenic emissions of CO_2 every year (Le Quéré et al., 2016). At present, a significant portion of this carbon uptake occurs in the Arctic Ocean, but sea-ice loss, surface warming, freshening, and a changing ecosystem are all likely impacting the magnitude of the Arctic CO_2 sink (Shuster et al., 2013; Bates & Mathis, 2009; McGuire et al., 2009). Ocean uptake of anthropogenic CO_2 results in the acidification of Arctic Ocean surface waters (Burt et al., 2016; Steiner et al., 2014; Azetsu-Scott et al., 2014; Azetsu-Scott et al., 2010; Yamamoto-Kawai et al. 2009), with potentially negative impacts on marine ecosystems (AMAP, 2013). Ongoing changes in the Arctic may also lead to increased air-sea exchange of other climate-active gases, such as dimethylsulfide (DMS), methane (CH_4) and nitrous oxide (N_2O) and organic aerosols. Production of DMS, a biogenic gas linked to cloud formation in the Arctic (Chang et al. 2011), is expected to increase as the sea ice cover recedes (Levasseur, 2013), while the release of CH_4, an important greenhouse gas, has been observed from sub-sea permafrost along the Siberian Arctic shelf (Shakhova et al., 2010). Additionally, organic aerosols in the atmosphere both contribute to Arctic haze and shield the surface from incoming solar radiation, acting to cool the climate, and are derived from both anthropogenic and natural terrestrial and marine sources (Russell, 2014).

This ArcticNet Phase III project studies the interactions of these climate-active gases, in addition to rates and patterns of ocean acidification. The project is aimed at synthesizing past results, while strategically filling remaining observational and data gaps. The project is structured around three integrated lines of investigation: (1) monitoring, (2) process studies, and (3) biogeochemical modeling.

ACTIVITIES

Ship Program: CCGS Amundsen

A portion of the 2016 ArcticNet cruise of the CCGS *Amundsen* was in partnership with the Canadian NETCARE and GEOTRACES projects. In addition, we collaborated with colleagues at Fisheries and Oceans Canada (DFO) to collect additional samples during the Joint Ocean Ice Study (JOIS) and C3O cruises on the CCGS *Louis St. Laurent* and CCGS *Laurier*. Significant synergy exists between this ArcticNet project and components of these networks. *Amundsen* cruise participants were from Université Laval, Dalhousie, McGill, University of British Columbia, University of Calgary and the University of Manitoba. The geographic foci of the cruise included the North West Passage of the Canadian Arctic Archipelago (CAA), Southern Beaufort Sea, Canada Basin, Baffin Bay and Nares Strait. Our team's activities onboard the *Amundsen* included:

- Measurement of dissolved CO_2 concentration in surface seawater using an automated flow through air-water CO_2 monitoring system;
- Water sampling from the ship's rosette for the determination of dissolved inorganic carbon (DIC), total alkalinity (TA), pH, $\delta^{18}O(H_2O)$, $\delta^{13}C(DIC)$, and aragonite saturation (Ω_{AR}) salinity, at select stations;
- Water sampling from the ship's rosette for the determination of vertical profiles of DMS and DMSP at select stations;
- High-frequency mapping of surface water concentrations of DMS using a sea-going automated cryogenic trap membrane inlet mass spectrometer (ACT-MIMS);
- Monitoring surface meteorology using sensors installed on a purpose-built tower located on the *Amundsen*'s foredeck, and on top of the ship's wheelhouse;
- Measurement of methane in surface water (5 m) and in the marine boundary layer along the entire cruise track;
- Vertical profiles of methane were collected at selected stations (mainly basic, full, and nutrient stations);
- Laboratory incubations were conducted to determine net production or consumption rates of methane and to assess the possibility of sulfur compounds (DMS, DMPS and DMSO) as precursors of methane using water samples collected from selected stations;
- Laboratory incubations were conducted to determine the impact of ocean acidification on productivity as well as DMS and DMPS production water samples collected in Baffin Bay; and
- Large volumes of the sea-surface microlayer were collected using an autonomous skimmer for comprehensive chemical analysis and experiments in an aerosol-generating wave tank;

Ship Program: R/V Martin Bergmann

One team member (B. Else), and several ArcticNet students (3) participated in a 1-week cruise onboard the R/V *Martin Bergmann*. The study focused on the southern Kitikmeot region, including Wellington Bay, Dease Strait, and Queen Maud Gulf, and included surveys along 4 transects, sampling near river mouths, sampling at a long-term ArcticNet monitoring station (Stn 315), recovery/re-deployment of acoustic receivers, and the installation of a land-based weather station. Samples for DIC, TA, $\delta^{18}O$ and several other parameters were collected at nine stations. The cruise allowed us to conduct detailed investigations of melt processes, and to extend a monitoring time series that was initiated from the Bergmann in 2013. The cruise also complemented the 2016 *Amundsen* expedition by visiting station 315 ahead of the *Amundsen*'s arrival in late August, and its return visit in late September. This sampling plan will provide a time series at this station that will be unique in its ability to measure processes from spring break-up through fall freeze-up in the western Arctic.

Green Edge

In collaboration with the Takuvik Laboratory, our team participated in the 2016 Green Edge Ice Camp campaign, near to Qikiqtarjuaq on Baffin Island, and cruise of the *Amundsen*. Takuvik Lab members collected water column samples for DIC and TA analysis throughout the late winter to early summer season. Those samples are now being analyzed, and will contribute to the overall goals of the GreenEdge campaign. On the *Amundsen*, between June-July 2016 in Baffin Bay (East of Qikiqtarjuak), our team undertook oceanographic sampling for DMS, DMSP and DMSO, pCO_2 and other carbonate parameters during several transits across ice-free to ice-covered waters of Baffin Bay.

Cambridge Bay Ocean Observatory and Ice Camp

We have deployed a number of CO_2 system sensors on the Ocean Networks Canada observatory in Cambridge Bay. In addition to providing a means to monitor changes in the CO_2 system at that location through the winter, the deployment is also serving to assess the behaviour of the sensors, thanks to discrete samples being collected year-round adjacent to the observatory by the staff of the Canadian High Arctic Research Station. A SeaFET pH sensor, a prototype Aanderaa pCO_2 optode, and a Pro-Oceanus CO_2 sensor were deployed in August and the data are available on the web in real-time.

One of our team members (Else) also led an 8-week sea ice field program in Cambridge Bay in support of these measurements, and in support of other ArcticNet projects (Barber – Sea ice processes).

Other Campaigns

We conducted sampling operations on the *Louis St. Laurent* and *Laurier* to augment our CH_4 and N_2O measurements across the Arctic Ocean. More than 500 discrete samples were collected in the field and returned to the laboratory at UBC where they were analyzed using automated purge and trap gas chromatography – mass spectrometry.

Additional laboratory experiments conducted at IOS (DFO – Sydney) are exploring the relationship between sea-ice formation rates and CO_2 export to the underlying water versus the atmosphere. Freezing experiments conducted at different, controlled ambient temperatures, coupled with discrete sampling and monitoring by in-situ instrumentation, allows carbon budgets to be constructed for each experiment.

Sea Ice and Ocean Modeling

Developments for the carbon cycle for the 1-D model include: the biological uptake of CO_2 in the coupled ice-ocean ecosystem, brine export (with DIC) to the underlying water column during ice growth, the release of melt water low in DIC during ice melt, a parameterization scheme for ikaite precipitation (within the ice) and dissolution (in the water column). Developments for the sulphur cycle include the implementation of DMS, DMSPp and DMSPd in the ice algae ecosystem (collaboration with CCAR-NETCARE). Multiple sensitivity studies have been performed for sea-ice algae, carbon and DMS parameterizations. Implementation of the sea ice ecosystem, carbon and DMS cycling in the 3-D model are underway.

RESULTS

Select results are organized under the sub-headings: carbon chemistry, micrometeorology, trace gases, and modeling. Results reported here include preliminary results associated with the recent field programs, and research that has made its way into peer-reviewed literature this reporting year from previous experiments. The team makes extensive use of both new data, and data archives pre-dating ArcticNet in support of contemporary process studies, and synthesis studies making sense of extraordinary spatial and temporal variability in the ocean's biogeochemical systems using the communities' data time series.

Carbon Chemistry

Ocean Acidification

The partial pressure of CO_2 in surface-water ($pCO_{2\text{-}SW}$), derived from pH and titration alkalinity measurements (TA) carried out in 2015, at sampling stations along the programme transect conform with results obtained using continuous, automated flow through air-water CO_2 monitoring systems operated by CEOS and UBC researchers. The aragonite saturation (Ω_A) depth shallows from east to west through Lancaster Channel, and is shallowest near McClure Strait, and in the south-eastern Beaufort Sea where Pacific waters upwell to depths of less than 50 m (Figure 1a,b,c). Long-term monitoring now reveals that the aragonite saturation depth has shallowed by nearly 500 m in the Canada Basin (Figure 1d).

In Hudson Bay we observed the variations in elements of the carbonate system (TA, DIC, $\delta^{13}C_{DIC}$ and Ω_{AR} in surface waters to, in most cases follow the distribution of salinity (reported in 2015 progress report). The exception was in proximity to the Nelson River estuary where we suspect the river water is high in TA relative to other plumes surveyed. Aragonite saturation (Ω_{AR}) was above 1 in surface waters (i.e., above saturation), however we observed the depth of Ω_{AR} to shoal within 20 m of the surface in south-eastern Hudson Bay (Figure 2).

Processing of 2016 data in Baffin Bay and Nares Strait is underway for carbonate species. In the late-spring (June) of 2016 the waters of western Baffin Bay were still capped by significant ice cover, whereas waters in the eastern Bay are ice-free. This is due to the large temperature difference between cold (-2 °C) Arctic outflow waters in the western bay, and warm (>3 °C) Atlantic-origin waters in the eastern bay. We found pCO_2 to be higher (300-350 uatm) in Arctic outflow waters of Pacific-origin in comparison to the Atlantic-origin waters (200-250 uatm) (Figure 3). We also observed a significant ice-edge bloom, which, in combination with the input of sea-ice melt at the surface, strongly decreased the pCO_2 within the marginal ice-zone. Further research is needed to understand the relative contributions of each to the observed decrease of pCO_2 in surface waters.

Process of air-sea gas exchange

During the 2016 cruise, sea-surface microlayer samples were collected and analyzed for surfactant activity (Figure 4) in order to investigate relationships between microlayer composition and air-sea CO_2 exchange rates. Duplicate samples from both the surface mixed layer and the microlayer were in general agreement with observations of Chl-a from the same samples, indicating a possible direct biological source of the surfactants. Such a biological source, as well as the often gelatinous nature of marine surfactants, are consistent with the relatively poor replication we observed at some stations. These results will be combined with literature data from laboratory studies on the extent to which surfactant enrichment in the microlayer retards air-sea gas exchange in a regional numerical model (in cooperation with Nadja Steiner) to estimate the extent to which surfactants may impact CO_2 exchange in the Arctic.

Developing Research in the Kitikmeot Region of the CAA

With four consecutive years of measurements in the southern Kitikmeot region, the annual cruises onboard the R/V *Martin Bergmann* are now revealing insights into the oceanography of this area. We have observed considerable variability in the spatial and temporal distribution of freshwater, and in the vertical temperature profiles (not shown). In the most recent cruise, the deployment of an underway pCO_2 system is allowing us to investigate the potential ramifications of freshwater in this region on air-sea CO_2 exchange. Although data are still being processed, preliminary results suggest that the impact of river discharge in this region is widespread, and leads to significant outgassing of CO_2.

Trace Gases

DMS

Results from the 2014 joint ArcticNet/NETCARE cruise of the *Amundsen* (Hussherr et al., 2017) show a linear decrease in mean concentrations of DMS with increasing concentrations of proton [H+] (decreasing pH –not shown), irrespective of light regime (high-light or low-light) experienced by the biological communities over the 9-day experimental assay.

Our team has shown marine sources of aerosols to contribute to cloud condensation nuclei in the Arctic (e.g., Chang et al., 2011). Yet processes that support the production of the gas are still not well understood

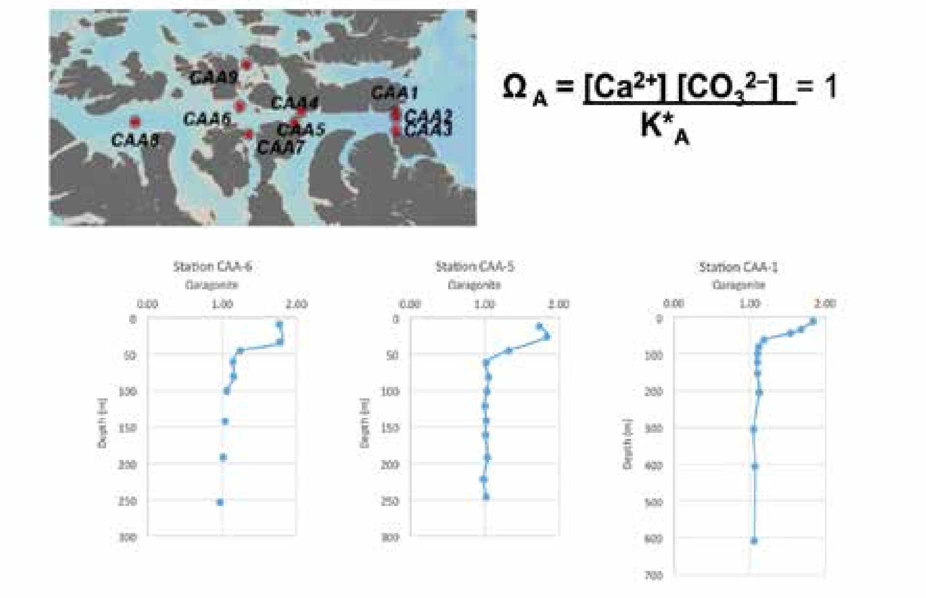

Figure 1a. Vertical profiles of the aragonite saturation state (Ω_A) of waters through the western CAA (Mucci, in prep.).

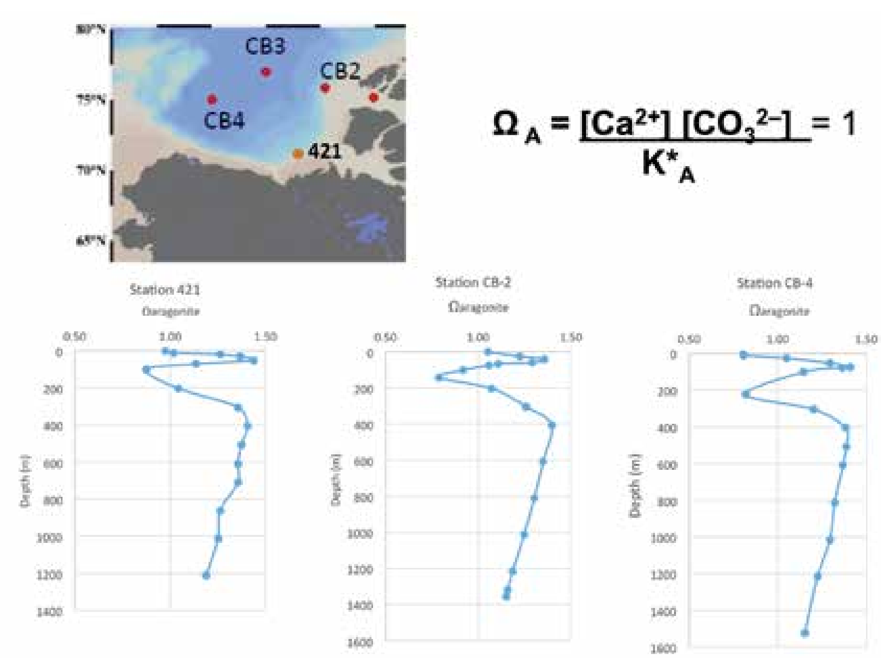

Figure 1b. Vertical profiles of the aragonite saturation state (Ω_A) of waters in the Canada Basin and south-western Beaufort Sea (Mucci, in prep.).

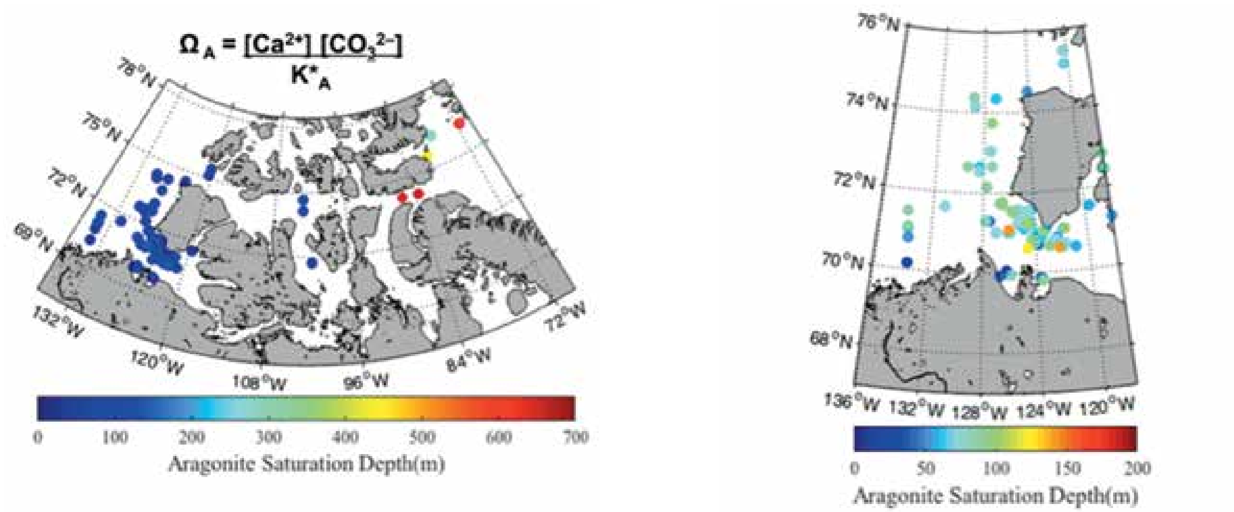

Figure 1c. Aragonite saturation (Ω_A) depth throughout the CAA and the eastern Beaufort Sea (Mucci, in prep.).

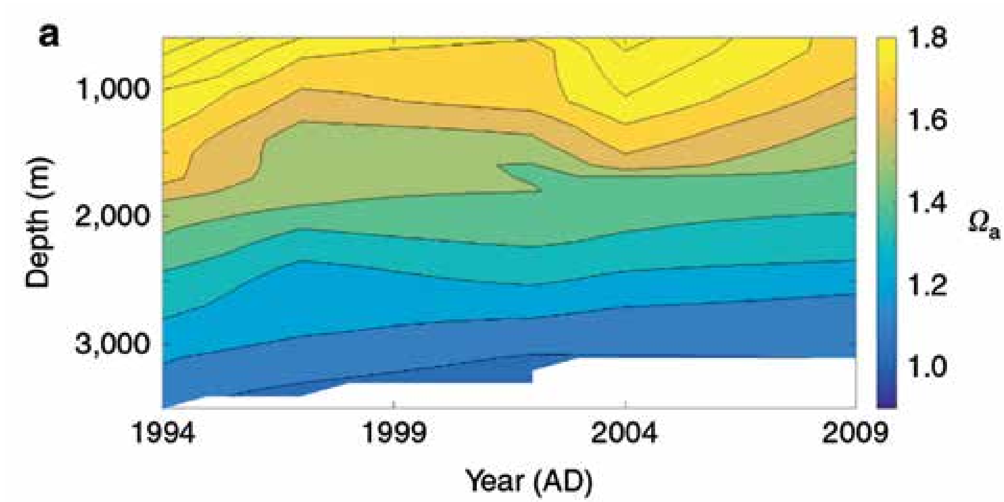

Figure 1d. Temporal evolution of the aragonite saturation (Ω_A) depth in the Canada Basin (from Luo et al., 2016). Note that field data show a 500 m rise in the saturation level over the 1995-2009 period. © Luo, Boudreau, Mucci, 2016.

and therefore the process is not well represented in biogeochemical models in polar regions. Preliminary results from the 2016 cruise show high spatial variability in near-surface concentrations of DMS associated with hydrographic frontal features, particularly strong haline gradients. Several inlets and fjords display high reservoirs of DMS suggesting a potentially overlooked source of reduced sulfur to the Canadian Arctic atmosphere in summer.

The observations shown in Figure 5 reveal high concentrations of DMS (10-20 nmol L^{-1}) in surface

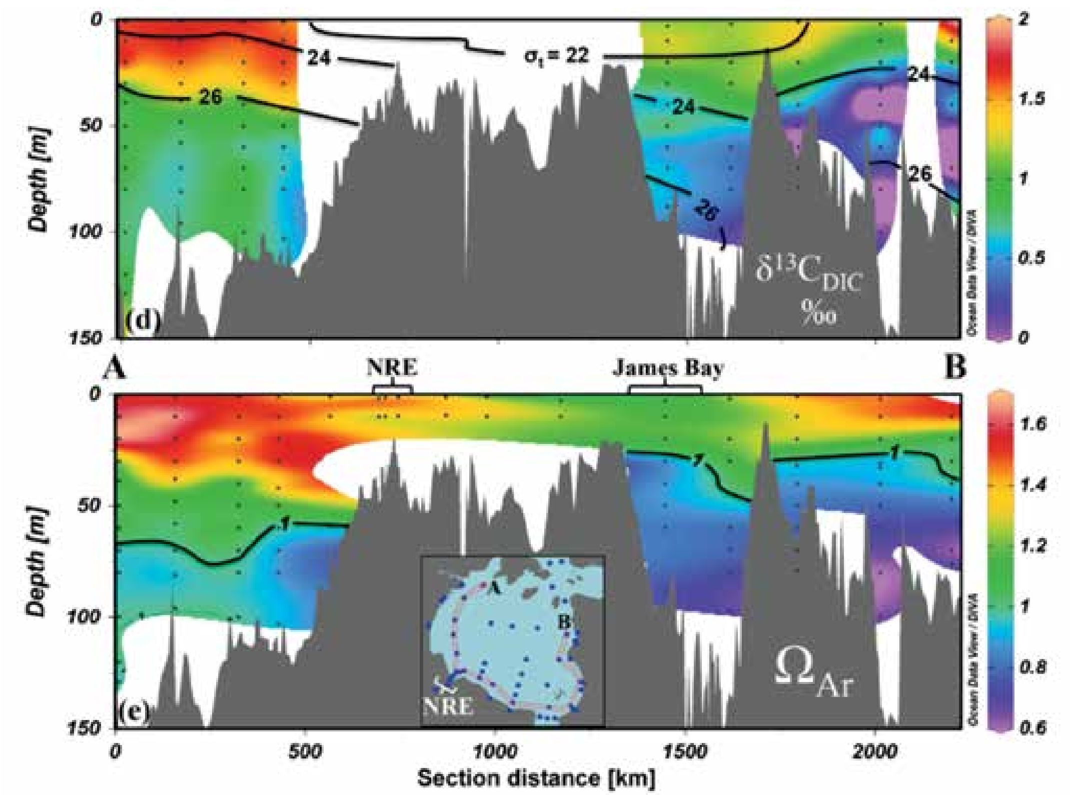

Figure 2. Cross section of $\delta^{13}C_{DIC}$ (upper panel) and Ω_{AR} (lower panel) along the coastal transect (inset in the lower panel). The solid line in the lower panel corresponds to the aragonite saturation horizon (Ω_{AR}=1) (Burt et al., 2016). © Burt, Thomas, Miller, Granskog, Papayriakou, Pengelly, 2016.

waters at the ice-edge as well as in ice-covered waters. Vertical profiles show that several sub-chlorophyll a maximums (SCM) can also be very rich in DMS (up to 60 nmol L^{-1}). In some instances, these very high concentrations of DMS seem to be associated with the abundance of the algae species, Haptophyte *Phaeocystis* sp., a well-known DMSP-producer. Well-established in other regions of the Arctic (e.g. in Seas east of Greenland), the increased occurrence of the colonial *Phaeocystis* in Baffin Bay may play an important role in shaping DMS distribution in this region of the Arctic in the future. Research along this line is underway.

CH_4

Research aims to understand the processes that determine the occurrence of CH_4 and nitrous oxide in the ArcticNet region. Both are more effective greenhouse warming agents relative to CO_2, yet little is known on the maritime Arctic's role in atmospheric budgets. Research was conducted on several coast guard ships in 2016, including the *Amundsen*, *Louis St. Laurent* and the *Laurier*.

During the ArcticNet cruise onboard the *Amundsen*, methane photoproduction was observed in samples collected from the Labrador Sea (Sta. 650), Baffin Bay (Sta. 108), Mackenzie Shelf (Sta. 434 and 428), and Canada Basin (Sta. 421). The photoproduction of methane increased linearly with added DMS. DMS is thus a precursor of methane photochemically produced. This phenomena has been previously undocumented.

During the 2016 Joint Ocean Ice Study (JOIS) cruise onboard the Louis St. Laurent, our team observed strong near surface sources of CH_4 (Figure 6) and N_2O (not shown). Isotope analysis of CH_4 reveals that oxidation

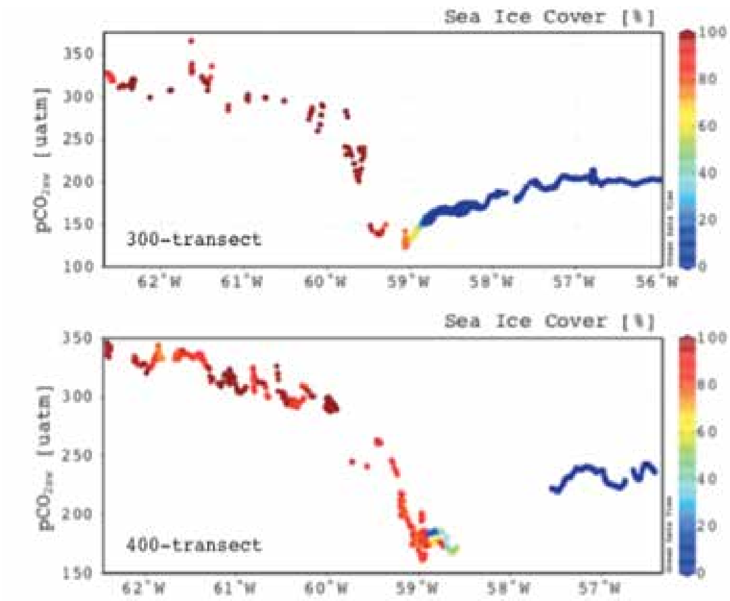

Figure 3. Surface water pCO_2 across two east-west transects in Baffin Bay during late-spring (June). Sea ice concentrations along the transects (from AMSR2) are represented by the color bar.

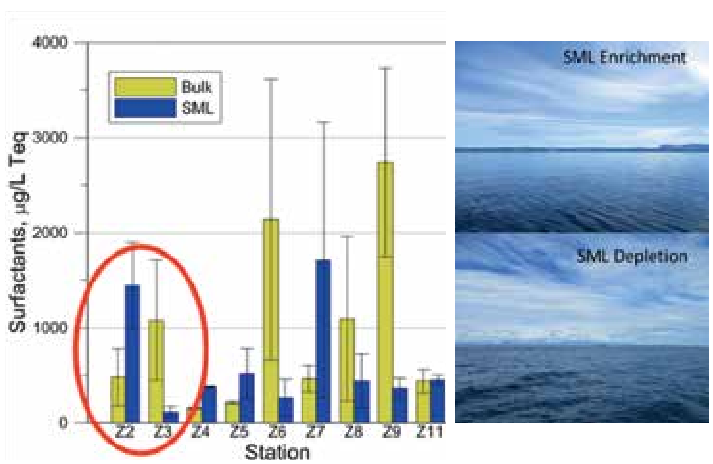

Figure 4. Distibutions of surfactions in the surface mixed layer ("bulk" waters) and the sea-surface microlayer during the joint ArcticNet-NETCARE expedition in Baffin Bay and the Canadian Arctic Archipelago during July and August, 2016. The photographs show surface conditions during sampling at stations Z2 (top) and Z3 (bottom).

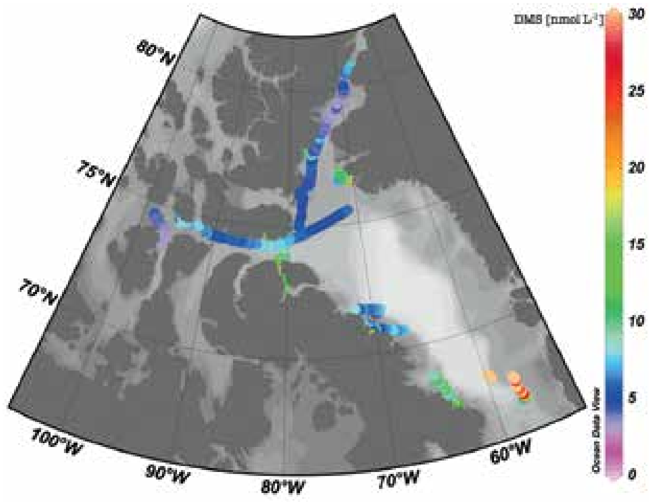

Figure 5. Spatial distribution of near-surface (ca. 5 m depth) concentrations of DMS (in nmol L^{-1}*) during the 2016 joint Netcare/ArcticNet campaign aboard the CCGS Amundsen (July-August 2016) (Lizotte et al., in prep).*

is a primary mechanism whereby CH_4 is removed from the water column (subsurface CH_4 maximum shown in Figure 6) and therefore limiting the outgas potential to the atmosphere.

Biogeochemical Modelling

Modelling activities work toward the refinement of a biogeochemical model (BGCM), optimized for Arctic seas and linking the atmosphere-ice-ocean cycles of carbon and sulphur. The implementation and coupling of a sea ice algae ecosystem and a pelagic ecosystem has been completed. The two systems are linked by the exchange of nutrients (mainly through diffusive flushing into the ice, and detrital release from the ice).

Results of the sensitivity studies of the BGCM (1D processes - Mortenson et al., submitted) indicate:

- (1) Ice algal growth limits subsequent pelagic biomass in the upper water column due to nutrient limitation, with a decrease of 50% of the maximum phytoplankton concentration in the upper 10 m in the standard run, relative to the run without ice algae.
- (2) Photosynthetic sensitivity and pre-bloom biomass determined the onset timing of the ice algae bloom.
- (3) The maximum biomass is relatively insensitive to the pre-bloom biomass.
- (4) A combination of linear and quadratic mortality rate parameterisations is required to adequately simulate the evolution of the ice algal bloom, indicating that processes associated with each of these functional forms are occurring within the ice algal bloom phase.

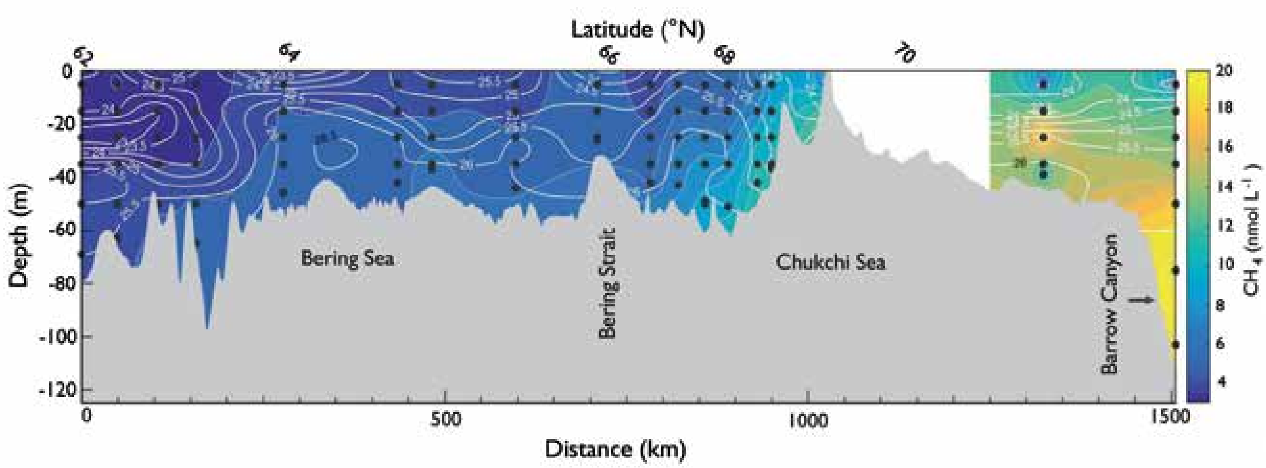

Figure 6. Methane distribution along a ~1500 km transect from the Bering to the Beaufort Sea (from Fenwick et al. 2017).

- (5) Large detrital (D2) sinking rates greater than a threshold of 15 m/d effectively strips the water column of the limiting nutrient after the bloom, transporting them to depth.

DMS model results (Hayashida et al. in revision) suggest that both sea-ice sulfur cycle and ecosystem have considerable impacts on the DMS production under the ice, and therefore should not be overlooked in the estimates of oceanic DMS fluxes. Specifically, the sea-ice sulfur cycle enhanced the under-ice DMS production directly by the release of bottom-ice DMSPd and DMS into the underlying water column, while the production was enhanced as well as reduced by the sea-ice ecosystem at various phases of the under-ice phytoplankton bloom. In the case of first-year land fast ice in Resolute Passage, we estimated that the incorporation of sea-ice sulfur cycle resulted in a 21% enhancement of DMS concentrations under the ice and a 24-30% enhancement of sea-air DMS fluxes during the melt period. Furthermore, in the vicinity of ice margins, the simulated spikes in sea-air fluxes of DMS originating from the bottom ice and underlying water column were comparable to some of the local maxima in the summertime fluxes estimated for ice-free waters in the Arctic.

A resulting standard simulation of carbon exchange in the marine Arctic is shown in Figure 7. Over the open-water season, cumulative carbon uptake (+ = into ocean) is around 850 mmol C m^{-2} (or ~ 10 g C m^{-2}), which is a reasonable value when compared to the estimated Arctic Ocean uptake reported by Takahashi et al., (2009).

In the seasonally ice covered Arctic Ocean, the effects of ice-ocean carbon exchange can persist in the surface waters into the open water season in mixed ice-ocean settings. How these processes occur, and if they have a substantial impact on air-sea exchange during the open water season, are questions that can be addressed by the 1-D model with carbon cycle implemented. On interest is learning how sensitive the air-sea exchange (during the open water season) is to the settling depth of expelled brine rich in DIC during ice growth. The simulated air-sea exchange of carbon is shown for five different runs (Figure 8, upper panel), with the depth of brine release ranging from the upper 10 metres to the 40-50 meter stratum, at 10-metre increments. Between the shallowest and deepest depths of simulated brine release, the resultant difference in oceanic carbon uptake is about 5% of the total (Figure 8 lower panel).

DISCUSSION

Year after year our team generates much needed 'new' information on biogeochemical cycles associated with the exchange of important climate-active gases. Studies described above provide incremental information on processes that underpin that transport and transformation of carbon species, and a much needed assessment of ocean acidification state within the bays and passages of the ArcticNet domain. Additionally, process relevant information (e.g., presence of surface surfactant, and role on air-sea exchange described above) supports the development of an Arctic marine ecosystem model, while data provides necessary information to develop parameterizations, and both initialize and validate the model as part of the Aquatic Climate Change Adaptation Services Program (ACCASP) at IOS (Fisheries and Oceans Canada and CCCma (Canadian Center of Climate Modelling and Analysis) as well as activities within the Arctic Monitoring and Assessment program (AMAP) for Arctic Ocean Acidification.

In the following results are discussed by theme. We elaborate on select issues below.

Carbon Chemistry

The Arctic Ocean represents an enhanced CO_2 sink relative to other world oceans (Shuster et al., 2013), and it naturally has a lower pH, Ω, and buffering capacity (lower alkalinity). Consequently the Ocean is vulnerable to ocean acidification, with studies, including those led by our group, already having confirmed that regionally waters are experiencing seasonal under-saturation for aragonite (Ω_{AR}) (e.g., Burt et al., 2016; Azetsu-Scott et al., 2014; Shadwick

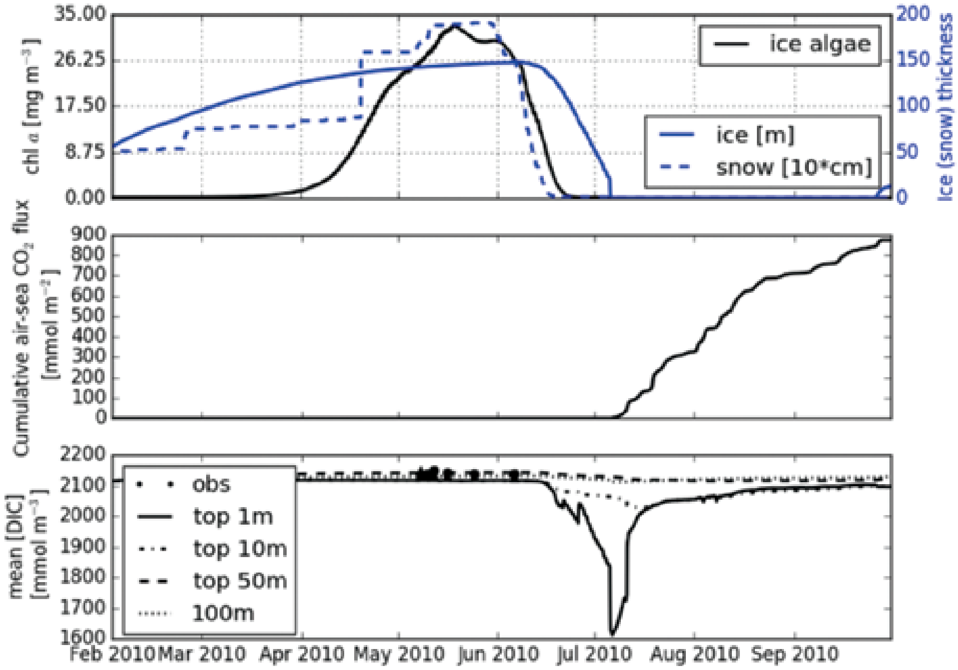

Figure 7. Ice, snow, and ice algae over the ice growth, ice melt and open water (top panel). Cumulative ocean carbon uptake (middle panel) and vertically-averaged [DIC] in the top 1 meter, 10 meters, 50 meters of the water column (lower panel). Black dots are measurements made by our team in the water column in near Resolute during a 2010 ArcticICE campaign (based on data presented in Brown et al. 2010).

et al., 2014; Azetsu-Scott et al., 2010; Chierici and Fransson, 2009; Yamamoto-Kawai et al. 2009). The CO_2 system can be particularly complex and therefore considerable variability is observed in place and time, particularly in coastal seas, where local controls (e.g., proximity to sea ice and river run-off, diverse metabolism associated with pelagic and benthic communities, CH_4 seeps, up-welling of low pH water, etc.) strongly influence the seawater carbonate system (Breitburg et al. 2015; Aufdenkampe et al. 2011; Durate et al., 2015). Contemporary models are not able to deal with the interplay of complex processes at scales appropriate for coastal systems (AMAP, 2013), which paradoxically can host taxa already stressed by development (e.g., changing land- and water-use within river catchments), and are thought the most vulnerable to OA (Duarte et al., 2015).

Our work incrementally is improving our understanding on those processes underpinning CO_2 exchange dynamics, regional status of OA, and rates of acidification across a variety of coastal shelf environments within the ArcticNet domain. Last we reported on research (Burt et al., 2016; Burger et al. in prep.) highlighting the strong influence freshwater has on surface pCO_2 (and hence air-sea exchange) in passages and bays of the eastern Canadian Arctic, and the surface distributions of carbonate parameters, including Ω_{AR}, throughout Hudson Bay. Burt et al., (2016) show that regionally within Hudson Bay the summertime aragonite saturation depth shoals to within 50 m of the surface. The same article exposes gaps in our understanding on regionally different influences of rivers on the marine system, and the likelihood of biased near surface measurements for variables like pCO_2 using traditional sampling systems like rosettes and underway systems in areas prone to freshwater lenses associated with sea ice melt and/or river inflow.

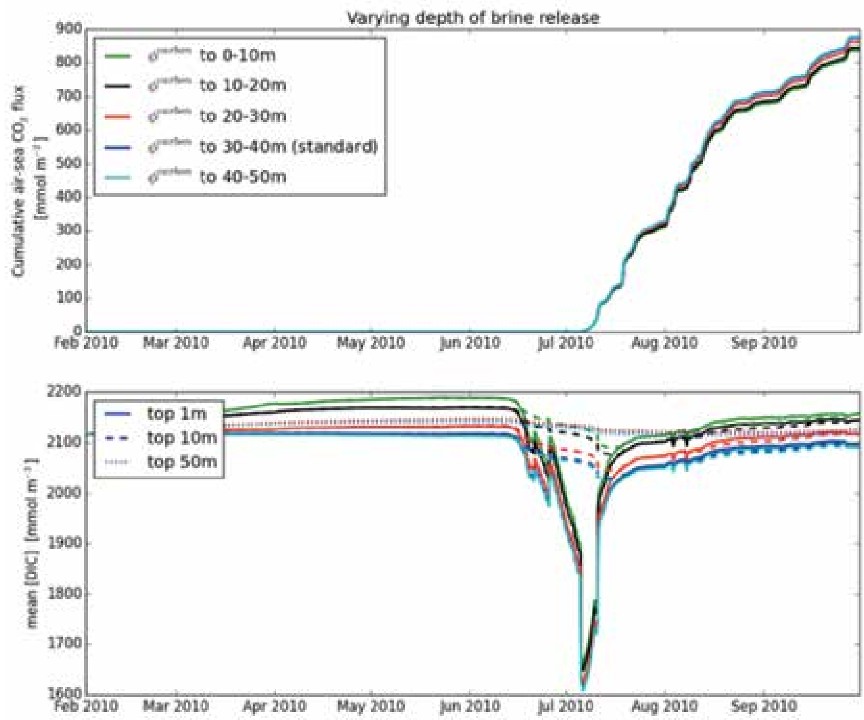

Figure 8. Cumulative ocean carbon uptake (top panel) and vertically-averaged [DIC] in the top 1 meter, 10 meters, 50 meters of the water column.

Preliminary results from the 2015 *Amundsen* cruise presented here shows a euphotic zone that is mostly undersaturated with aragonite of anthropogenic eastern Beaufort Sea, attributed to the uptake of CO_2, addition of sea-melt waters and the upwelling of Pacific waters. Whereas the aragonite saturation depth shallows westward throughout the CAA, surface waters remain supersaturated with respect to aragonite due to limited freshwater input. Long-term monitoring now reveals that the aragonite saturation depth has shallowed by nearly 500 m in the Canada Basin and our box-model model results (Luo et al., 2016) indicate that it results from the intrusion of pre-acidified Atlantic waters at mid-depths in the Arctic Ocean basins. The travel time of these waters from the North Atlantic to the Canada Basin was estimated at less than 20 years (Jack Cornett, pers. comm.). Research will continue in 2017 to shore up our understanding in particular on the influence of freshwater in Hudson Bay (joint with the BaySys project), Baffin Bay and the CAA. A synthesis of OA state in the CAA using our time series is underway in collaboration with DFO in support of marine protected areas program, and information generated by our group significantly contributed to the recent AMAP ocean acidification assessment in the Arctic (AMAP, 2013).

Trace Gases

As a whole, results from this sub-project suggest that sea-ice dynamics exert a strong influence on arctic microbial communities and their production/emission of DMS. Measurements from the 2016 campaigns corroborate the hypothesis suggesting that ice-edge blooms are significant reservoirs of DMS. Moreover, our study reveals that waters underlying sea-ice (including dome waters under ponded ice) are as rich in DMS as their ice-free counterparts suggesting potentially important pulsed effluxes of DMS during ice break-up and the establishment of leads and cracks. Brackish melt ponds harbor DMS-producing communities and thus represent an additional source of DMS in direct contact with the atmosphere. The anticipated proliferation of arctic melt ponds (Palmer et al. 2014) may play a relevant role in spring-summer dynamics of DMS in the future. An unexpected outcome of the 2016 campaign was the detection of high DMS under a giant decaying ice floe (a difficult medium to sample from traditional ice camps in view of its high instability). Preliminary results suggest that strong haline stratification under melting floes may result in the entrapment of microbial communities within highly irradiated under-ice waters and a resulting up-regulation of photo-protective mechanisms including DMS production. Finally, high spatial resolution measurements allowed the detection of large variability in DMS over small scales, as well as strong near-surface DMS gradients across hydrographic fronts and transitional areas between open water and oceanic inlets and fjords. Near-terrestrial sources of DMS had never been surveyed at such fine scale thus far in the Canadian Arctic Archipelago and the high concentrations measured (up to 30 nmol L^{-1}) warrant further investigation into these regions role as significant emitters of DMS during summer.

The study by Hussherr et al. (2017) specifically addresses the response of DMS dynamics to ocean acidification and light regime in Arctic waters. A phytoplankton bloom dominated by diatoms took place in all experimental gas-tight bags, leading to an increase in DMSP concentrations with variations in responses attributed to pH treatments while no clear effect of light regimes was observed. DMS concentrations significantly decreased with decreasing pH, a result which is in agreement with the only other study of its kind in Arctic waters (Archer et al. 2013). The results from our team's study suggest that ocean acidification may lower DMS concentrations during arctic blooms in the future, with possible implications for the Arctic climate.

CONCLUSION

Research has shown to date that the biochemical controls over the exchange of climate relevant gases is highly variable across the ArcticNet domain, and with season. Status of acidification across the domain that we've sample is likewise variable. On the latter surface waters regionally have seasonally become undersaturated with respect to aragonite, while in deep waters the aragonite saturation horizon is rising, and projected to reach the base of the surface mixed layer by 2140 (Luo et al., 2016). Aragonite-secreting organisms therefore maybe threatened on long timescales.

Work remains to generate new information on key controls to better our ability to forecast the response of the biogeochemical system to regional changes in the Arctic climate. Knowledge arising from our work seamlessly informs the development of an Arctic marine ecosystem model, while data provides necessary information to develop parameterizations, and both initialize and validate the model as part of the Aquatic Climate Change Adaptation Services Program (ACCASP) at IOS (Fisheries and Oceans Canada and CCCma (Canadian Center of Climate Modelling and Analysis) as well as activities within the Arctic Monitoring and Assessment program (AMAP) for Arctic Ocean Acidification. Regionally, work is needed in less studied regions, including Hudson Bay, Baffin Bay, and Nares Strait/Kennedy Channel, and the Kitikmeot region of the CAA. As freshwater strongly impacts many facets of biogeochemical cycling, important research remains to improve our understanding on the role of freshwater associated with its many sources, on the cycling of carbon, sulfur and nitrogen, including state and risk of acidification.

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ARCTIC GEOMICROBIOLOGY AND CLIMATE CHANGE

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ABSTRACT

This research project will focus on physical and chemical processes in sea ice that affect the vertical transport of mass and energy. Despite sophisticated model predictions of the global climate including the Polar Regions major gaps in basic sea ice knowledge exist. While the conceptual framework for greenhouse gas transport is increasingly supported by observations there are still major unknowns. In fact, the transport of any material (gases, liquids, and precipitates) through sea ice is poorly understood. Even the release of brine from sea ice to the underlying ocean is poorly studied, especially with respect to its seasonal evolution and kinetics of formation. The objective of our project is to investigate and quantify the importance of fundamental biogeochemical processes using state-of-the-art assessment techniques in a comprehensive three-pronged approach linking small-scale ice tank (cold rooms), meso-scale ice tank (SERF) and in situ sea ice studies. Specifically, we have two major goals, which relate to climate change impacts in the Arctic: (a) To investigate transport processes, and biogeochemical modification of solutes and precipitates associated with thin ice in polynyas and leads, and (b) to investigate the impact of increasing snow cover on biological, chemical, and transport processes within sea ice.

KEY MESSAGES

Sea Ice Biogeochemical Cycling

- Freshwater from sea ice melt and river runoff strongly affects the partial pressure in CO_2 of surface seawater (pCO_2^{sw}) and therefore the air-seawater CO_2 fluxes. From summer to autumn, the Canadian Arctic Archipelago (CAA) acted as a sink for atmospheric CO_2 of about -11 mmol m^{-2} d^{-1}.
- Ikaite concentration could be deduced using dissolved inorganic carbon, a new and fast method to measure ikaite in sea ice.
- New non-destructive imaging technic using X-Ray tomography is suited to characterize air inclusions (i.e bubbles) in sea ice.

Sea Ice Physical Properties and Processes

- The extremely cold winter over North America is significantly correlated with summer sea surface temperature over the Barents Sea.
- The summer sea ice extent trends of both Hudson Bay and the Arctic Ocean are well correlated to the atmospheric circulation.

Hydrodynamic of Arctic shelf seawater and fjords system

- Tidal pumping is a major source of dense water that drives fjord circulation during ice covered period and influence ice thickness patterns.
- The Wandel Sea shelf subsurface layer (20-70 m depth) is comprised of Pacific origin water.
- Ocean-glacier interaction generates intrusions and modifies mixing beneath the glacier depth.

Ice Algae and Under-ice Algal Blooms

- The competing influences of algal photosynthesis and bacterial respiration affect carbon fluxes between the ice and surrounding environments.
- Quantifying the contribution of the ice community to carbon exchange is an important step towards improving sea ice flux models.
- Determination of photo-protective capacities of algae will strengthen the climate change models by taking into account algal physiological changes depending on the light.

OBJECTIVES

Sea Ice Biogeochemical Cycling

New 2016 objectives:

1. Monitor the spatial and temporal variability of pCO_2^{sw} within the Canadian Arctic and examine the response of pCO_2^{sw} to conditions associated with summer ice melt and initial sea ice formation during the autumn.

Pursuit of past years' objectives:

2. Identify ikaite crystals in sea ice and develop a new method of quantifying their concentration.

3. Develop a new methodology to study air porosity in sea ice, identifying and quantifying sea ice air volume fraction and gas content.

Sea Ice Physical Properties and Processes

1. Understand the mechanisms of recent climate variability at mid- and high- latitudes and their effect on Arctic sea ice extent.

Oceanographic Research

1. Create a full seasonal and spatial dataset of fjord hydrodynamics (Young sound area, Greenland).

2. Investigate the principal features of vertical profiles of salinity and temperature taken over the shelf regions deeper than 100 m associated with cross-slope and ocean-glacier interactions (Wandel sea shelf Area, Greenland).

Ice Algae and Under-ice Algal Blooms

Pursuit of objectives from past years:

1. To investigate the use of oxygen optodes in quantifying sea ice primary production.

2. Assess the dominant environmental factors driving variability in sea ice productivity.

3. Characterize changes of photosynthetic parameters of ice algae during spring and link to the environmental conditions.

An *in situ* experiment was conducted to improve our knowledge on the under-ice blooms which are challenging to monitor:

4. To compare the bacterial and primary production between two simulated under-ice blooms exposed to different nutrient conditions.

KNOWLEDGE MOBILIZATION

Presentations at scientific conferences

- BEPSI Meeting, Working group on sea ice biochemistry, Paris, Mars 2016;
- EGU 2016 General Assembly in Vienna, Austria, May 2016;
- UArctic Congress 2016 in St. Petersburg, Russia, September 2016;
- Arcticnet 2016, Winnipeg, Manitoba, Canada, December 2016.

Outreach activities

- Invited guest lecture in high school class in Nuuk, Greenland, February 2016;
- Invited guest lectures on two master classes at Greenland Institute of Natural Resources and University of Greenland, May 2016;
- Arctic Science day, High school students, Winnipeg, Manitoba, Canada, March 2016;
- University of Manitoba Science Rendez-vous, adults and youths, Winnipeg, Manitoba, May 2016;

- Workshop on Green Edge field program, June 2016;
- Ice coring and the complexity of sea ice" with students from Qikiqtarjuak Nunavut, June 2016;
- Inspiration lecture of Arctic Science in primary school, August 2016;
- Arctic Climate Change Youth Forum (ACCYF), Winnipeg, Manitoba, Canada, December 2016.

INTRODUCTION

Sea Ice Biogeochemical Cycling

Bates and Mathis (2009) estimated that the Arctic Ocean absorbs from -66 to -199 Tg C yr^{-1}. However, their estimate is based only on the ice-free season and is therefore probably significantly underestimated. The limited data available indicates that much of the western Arctic Ocean may be a net CO_2 sink throughout the year (e.g., Mucci et al., 2010; Shadwick et al., 2011; Evans et al., 2015). Bates et al. (2006) have suggested that reduced sea-ice extent in the Arctic Ocean could increase oceanic CO_2 uptake in the Arctic, largely because of increased primary production. The Arctic Ocean, and the Canadian Arctic Archipelago (CAA) represents about 20% of the total Arctic continental shelf area (Carmack et al., 2006). However, the overall biogeochemical role of the CAA in the Arctic Ocean is still poorly understood. Continental shelves are of particular interest in the global carbon cycle as carbon transport and sequestration processes tend to be amplified in these areas (Tsunogai et al., 1999). To examine the role of the CAA in the Arctic Ocean, we monitored the spatial and temporal variability of pCO_2^{sw} within the Canadian Arctic.

Ikaite ($CaCO_3 \cdot 6H_2O$) is a metastable calcium carbonate mineral which precipitates out of sea ice (Assur, 1958). Ikaite has been observed in both Antarctic and Arctic sea ice (Dieckmann et al., 2008) and may play a significant role in the sea ice carbon pump (Parmentier et al., 2013; Rysgaard et al., 2011). To increase the understanding of its role in the sea ice carbon pump, a new method of quantifying ikaite in sea ice was developed and compared with the method currently in use, which consists of image analysis of small quantities of ice (Rysgaard et al., 2013). The new method uses dissolved inorganic carbon (DIC) analysis of filtered ikaite crystals. This method was tested in first and multi-year sea ice near Station Nord, Greenland in April 2015 and in first year sea ice near Cambridge Bay, Nunavut in May 2016 and compared with the image analysis technique to determine the effectiveness of the DIC method of determining ikaite concentration.

The presence of a gas phase in sea ice creates the potential for gas exchange with the atmosphere; the formation of air inclusions and transport of gases within sea ice is still poorly understood. The lack of detailed description of gas filled porosity is in large part due to methodological challenges. Crabeck et al. (2016) proposed methodological improvements to the measurement of air inclusions within sea ice. The limitations of thin section microscopy motivated the use of non-destructive computed tomography (CT) X-ray imaging.

Sea Ice Physical Properties and Processes

One of the manifestations of recent climate change in the Northern Hemisphere is the rapidly declining Arctic ice pack and warming of high-latitudes (Ogi and Wallace, 2007; Screen & Simmonds, 2010; Stroeve et al., 2012). A number of previous studies have presented possibilities that the melting of Arctic sea ice and the associated Arctic warming is responsible for the recent extreme weather and the climate variabilities at mid-latitudes (Francis and Vavrus, 2012; Tang et al., 2013). Changes in the Arctic environments (decrease of sea ice, warmer sea surface temperature) affect biological and biogeochemical processes (Barber et al., 2015). Hence, we examine the variations of temperatures over the Greenland and North America associated with sea ice extents in the Arctic Ocean to anticipate future changes in the Arctic environments.

Oceanographic Research

One of the most significant global issues over the last decade has been the vast change in the Arctic region. The Arctic Science Partnership (ASP) consortium (www.asp-net.org) was established to understand connections and processes linking climate, cryosphere, ocean and ecosystems. Under the framework of ASP, an extensive oceanographic field campaign took place during May 2014 in Young Sound, Greenland and over the spring 2015 across shelf of the Wandel Sea, Greenland. Fjords around Greenland connect the Greenland Ice Sheet to the ocean and their hydrography and circulation are determined by the interplay between atmospheric forcing, runoff, topography, fjord-shelf exchange, tides, waves, and the seasonal growth and melt of sea ice. Limited knowledge exists on circulation in high-Arctic fjords, especially during winter, when they are covered with sea-ice and freshwater input is low.

Ice Algae and Under-ice Algal Blooms

In the ice-covered central Arctic, up to 57% of primary production is associated to ice algae (Gosselin et al., 1997; Arrigo et al., 2010). The growth of ice algae is mainly influenced by two key parameters: the light, which determines the beginning of the algal growth, and the nutrients, mostly influencing the bloom duration. Important variations of light conditions are observed in sea ice during spring, from important snow pack conditions (low light) to the formation of meltponds (high light). Thus sea ice microalgae possess high photosynthetic plasticity to acclimatize and protect themselves. However, Petrou et al. (2011) showed that the plasticity and photoacclimation of Antarctic diatoms depend of their niche habitats. Thus ice algae in the bottom sea ice and sinking could possess different capacities of photoacclimation. Previous studies in Antarctic showed that the sympagic pennate diatoms have higher photoprotection capacities, but no study has compared the plasticity of both communities (ice algae vs phytoplankton) at the same time. Because of the actual retreat and thinning of sea ice, it becomes essential to understand the photoprotection mechanisms and the evolution of photosynthetic properties of algal communities.

In addition, in the last few years, under-ice blooms have been increasingly observed at the end of spring, when light penetrating through the ice is sufficient to support algal growth (Arrigo et al., 2012). They play an important role in the Arctic marine ecosystem but remain challenging to monitor. These under-ice blooms can be composed of different algal communities: phytoplanktonic centric diatoms vs sympagic pennate diatoms as observed in Resolute Passage by Galindo et al. (2014). Our study has for objective to evaluate the impact of under-ice blooms on the biological carbon pump.

ACTIVITIES

Sea Ice Biogeochemical Cycling

Geilfus published a manuscript regarding the export of ikaite from new and young sea ice: Geilfus N-X, Galley RJ, Else BGT, Karley Campbell, Papakyriakou T, Crabeck O, Lemes M, Delille B, Rysgaard S (2016) Estimates of ikaite export from sea ice to the underlying seawater in a sea ice–seawater mesocosm The Cryosphere, 10, 2173–2189, 2016. This manuscript was based on data collected during the Sea-ice Environmental Research Facility (SERF) experiment in January 2013. Geilfus worked on a new manuscript focused on the spatial trends in pCO_2^{sw} across the CAA. Data were collected aboard the CCGS *Amundsen* in the summer (27 July to 11 August) and autumn (4-22 October) of 2011 during the ArcticNet cruise across the CAA.

The method to determine ikaite precipitation developed in 2015 and tested first at the Sea-Ice Environmental Research Facility (SERF) at the University of Manitoba in early February 2015 and at Station Nord, Greenland in April 2015, has been applied at Cambridge Bay, Nunavut in May 2016. A paper is in preparation by Kyle and should be submitted soon.

Crabeck published a manuscript on CT X-ray method to quantify air volume fraction: Crabeck C, Galley R, Delille B, Geilfus N-X, Lemes M, Else B, Tison J-L, Francus P, Rysgaard S (2016) Imaging air volume fraction in sea ice using non-destructive x-ray tomography. The Cryosphere. 10, 1125–1145, doi:10.5194/tc-10-1125-2016. This manuscript was based on data collected during the Sea-ice Environmental Research Facility (SERF) experiment in January 2013. During 2016, Crabeck applied the method to ice collected in Young Sound, Greenland, 2014 and in Station Nord, Greenland 2015.

Sea Ice Physical Properties and Processes

Ogi worked on the sea ice extent data from 1979 to 2014 obtained from the National Snow and Ice Data Center and data of atmospheric fields from the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis data set from 1979 to 2014, as well as on data of monthly surface air temperatures from coastal Greenland stations from the Danish Meteorological Institute historical climate data-collection. Ogi published the following manuscripts:

Ogi M, Rysgaard S, Barber DG, Nakamura T, Taguchi B (2016) Is summer sea surface temperature over the Arctic Ocean connected to winter air temperature over North America? Climate Research, 70(1):19-27, doi:10.3354/cr01412.

Ogi M, Rysgaard S, Barber DG (2016) The influence of winter and summer atmospheric circulation on the variability of temperature and sea ice around Greenland. Tellus A, 68, 31971, http://dx.doi.org/10.3402/tellusa.v68.31971.

Ogi M, Rysgaard S, Barber DB (2016) The impact of the Tropical/Northern Hemisphere teleconnection pattern on an abnormally cold winter over North America. The Open Atmospheric Science Journal 10: 14-25. Doi:10.2174/1874282301610010006.

Ogi M, Barber DG, Rysgaard S (2016) The relationship between summer sea ice extent in Hudson Bay and the Arctic Ocean via the atmospheric circulation. Atmospheric Science Letters. doi:10.1002/asl.709.

Ogi M, Rysgaard S, Barber DG (2016) Importance of combined winter and summer Arctic Oscillation (AO) on September sea ice extent. Environmental Research Letters, 11, 034019, ERL-102020, doi:10.1088/1748-9326/11/3/034019.

Oceanographic Research

Following the Young Sound campaign in may 2014, we carried out the analysis of seasonal observations of circulation, hydrography and cross-sill exchange of the Young Sound-Tyrolerfjord (74°N) in NE Greenland. A manuscript has been submitted by Boone: Boone W., Rysgaard S., Kirillov S., Dmitrenko I., Bendtsen J., Mortensen J., Meire L., Petrusevich V., Barber D., Circulation and fjord-shelf exchange during the ice covered period in Young Sound-Tyrolerfjord, NE-Greenland (74°N), submitted to Estuarine, Coastal and Shelf Science.

New samplings were performed from the new Villum Research Station located at the Danish military outpost Station Nord at 81°36N, 16°40W. This research is focused on analysis of the first-ever conductivity-temperature-depth (CTD) observations on the Wandel Sea shelf collected from the landfast ice in April-May 2015. They were complemented by CTDs taken in June-July 2015 over the Wandel Sea continental slope during the Norwegian FRAM 2014-15 sea ice drift. These CTD profiles are clustered based on the occurrence of thermohaline intrusions that are used as tracers of the ocean-glacier and shelf-slope interactions. The following manuscript has been submitted to Journal of Geophysical Research – Oceans: Dmitrenko, I. A., S. A. Kirillov, B. Rudels, D. G. Babb, L. Toudal Pedersen, S. Rysgaard, D. G. Barber and Y. Kristoffersen (2017), Tracing the Arctic Ocean outflow and the glacier-ocean interaction over the Wandel Sea shelf (Northeast Greenland), J. Geophys. Res., manuscript under review.

Ice Algae and Under-ice Algal Blooms

Based on data collected in Dease Strait approximately 15 km offshore from the community of Cambridge Bay, Nunavut from March to June, 2014. Campbell published manuscripts about the use of oxygen optodes to monitor sea ice gross primary production and net community production and two others manuscripts about environmental factors that impact primary productivity of sea ice algae are under review:

Campbell, K., C.J. Mundy, J.C. Landy, A. Delaforge, and S. Rysgaard (2016), Community dynamics of bottom-ice algae in Dease Strait of the Canadian Arctic, Prog. Oceanogr. 149, 27-39, doi: 10.1016/j.pocean.2016.10.005.

Campbell, K., Mundy, C.J., Belzile, C., Delaforge, A. and S. Rysgaard (2017a), Seasonal dynamics of algal and bacterial communities in Arctic sea ice under variable snow cover, Polar Biol. (in review).

Campbell, K., Mundy, C.J., Gosselin M., Landy, J.C., Delaforge, A. and S. Rysgaard (2017b), Net community production in the bottom of Arctic sea ice over the spring bloom, Geophys. Res. Lett. (in review).

New sampling was conducted from an ice station located near Davis Strait, offshore from the community of Qikiqtarjuak, Nunavut (67°29.23N, 63°38.00W) during the Green Edge project. From 2 May to 8 July 2016, seawater, sea ice and fresh sediment traps were collected. For each sample, the maximum photochemical efficiency of PSII and induction curves were measured using a pulse-amplitude modulated (PAM) fluorometer (Water-PAM, Heinz Walz) as a non-intrusive approach. In addition, a 16 days experiment was conducted in in situ conditions to compare the growth properties of two under-ice blooms in different nutrient conditions.

RESULTS

Sea Ice Biogeochemical Cycling

In summer across the CAA, pCO_2^{sw} was undersaturated with respect to the atmosphere except in Coronation Gulf, where concentrations up to 419 µatm were observed (Figure 1a). Average pCO_2^{sw} ranged from 224 µatm (in the Parry Channel) to 384 µatm (in Coronation Gulf). In the autumn, pCO_2^{sw} was undersaturated with respect to the atmosphere across the entire cruise track, ranging from 237 to 341 µatm (Figure 1a), thus over a smaller range than during the summer. As the pCO_2^{sw} was mainly undersaturated during both the summer and the autumn, the CAA, as a whole, acted as a net sink for atmospheric CO_2, with uptake up to -108.5 mmol m^{-2} d^{-1} (Figure 1b). However, seawater CO_2 supersaturation in Coronation Gulf during the summer did imply a CO_2 release from the ocean to the atmosphere up to 3.7 mmol m^{-2} d^{-1}.

Calculated ikaite concentration using image analysis ranged from 0.1±0.1 to 261.7±306.5 µmol kg^{-1} in first year sea ice and 0 to 1.4±2.1 µmol kg^{-1} in multi-year sea ice. Calculated ikaite concentrations using DIC analysis of filtered crystals ranged from 1.8±0.1 to 69.5±60.7 µmol kg^{-1} in first year sea ice and from 1.8±0.9 to 7.8±4.7 µmol kg^{-1} in multi-year sea ice. In general, ikaite concentrations calculated using DIC analysis of filtered crystals were lower than those calculated using image analysis in first year sea ice. In multi-year sea ice, ikaite concentrations calculated using DIC analysis were generally higher than those calculated using image analysis. In all cases, ikaite concentrations calculated using both techniques agreed within two times the standard error.

CT X-ray imaging is a reliable non-destructive method to identify and quantify the air volume fraction in sea ice. CT-imaged sea ice air-volume fractions were always lower than 2% in columnar sea ice but systematically exceeded 5% in granular sea ice near the sea ice-atmosphere interface. Air volume fraction increased as ice grew thicker in columnar and granular sea ice.

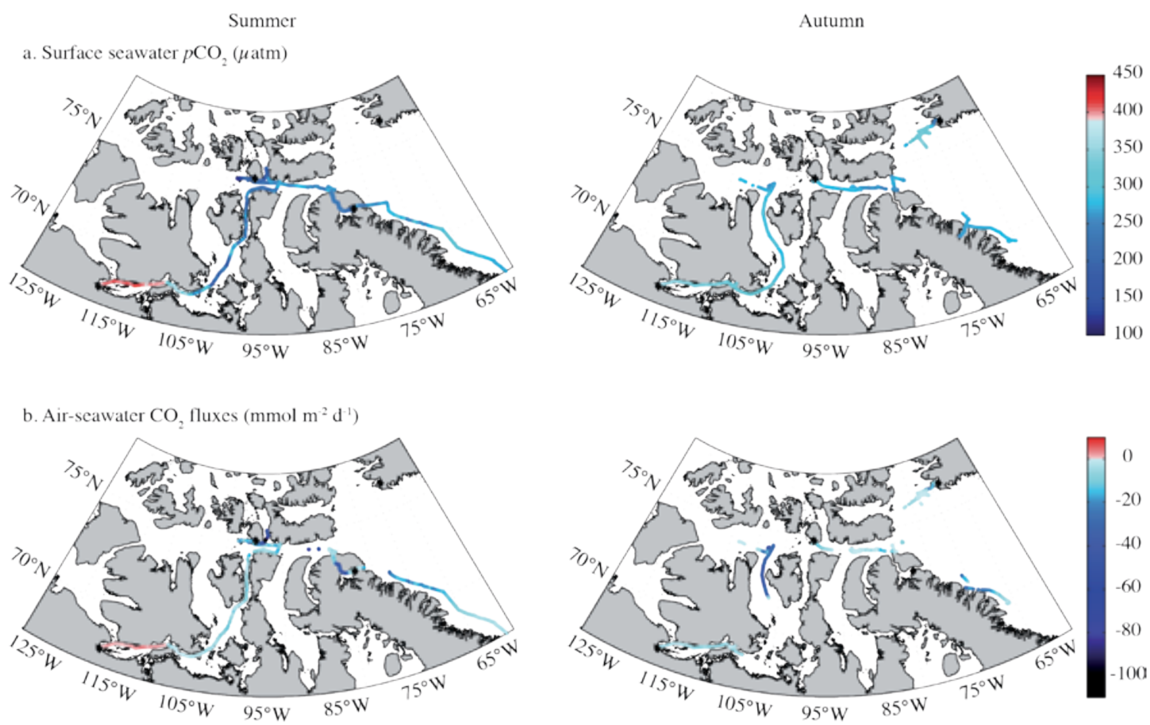

Figure 1. (a) Surface seawater pCO_2 (pCO_2^{sw}) measured at 5 m depth and (b) air-sea CO_2 fluxes (in mmol m^{-2} d^{-1}) along the ship track during both the summer (left) and autumn (right).

Sea Ice Physical Properties and Processes

During winter, the Greenland station temperatures and sea ice extent are correlated with the surface air temperatures over Baffin Bay and Davis Strait. The winter atmospheric patterns associated with these Greenland station temperatures and sea ice extents show positive anomalies over the Arctic and negative anomalies over the North Atlantic. During summer, the surface air temperature anomalies associated with all Greenland station temperatures and sea ice extents surrounding Greenland have positive anomalies over mid-latitudes. The variability of summer sea ice extent in both Hudson Bay and the Arctic Ocean are well correlated and have a strong negative trend. The negative sea ice extent trends are associated with a summer atmospheric circulation pattern that is characterized by positive anomalies over the Arctic Ocean and negative anomalies over mid-latitudes.

Oceanographic Research

During the Young Sound campaign in May 2014, distinct seasonal circulation phases are identified and related to polynya activity, meltwater and inflow of coastal water masses. Renewal of basin water in the fjord is a relatively slow process that modifies the fjord water masses on a seasonal timescale.

Findings from Wandel Sea area

(i) The sub-surface (15-70 m depth) “cold Halostad” layer with salinities of 30-31.5 and associated underlying Halocline layer is a distinct feature of the Wandel Sea shelf hydrography (Figure 2). It does not persist over the Wandel Sea continental slope, indicating the water masses over the shelf and slope have different origins. A similar water mass structure was observed downstream in the Northeast Water Polynya area. This structure is likely maintained by the coastal branch of the

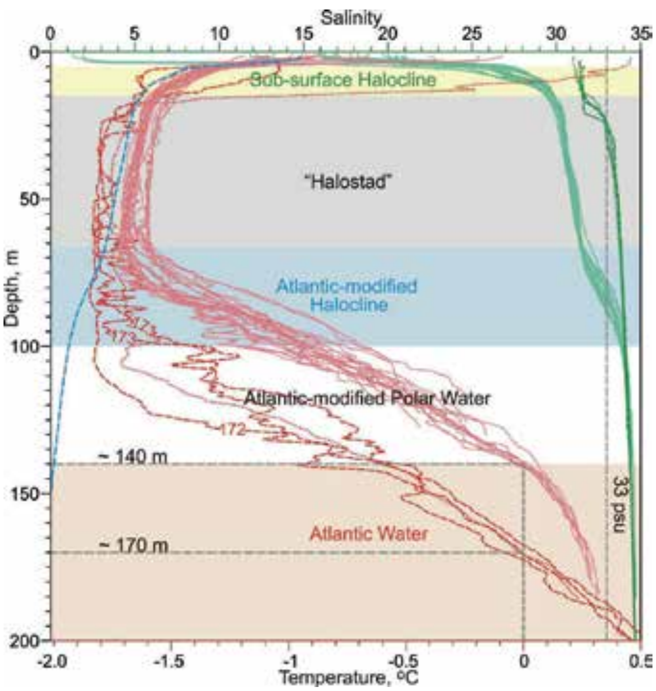

Figure 2. Vertical distribution of temperature (red) and salinity (green) profiles over the Wandel Sea shelf (≥ 100 m depth; solid curves) from April and May 2015, over the continental slope (stations 171-173; dashed curves) from June and July 2015 from the Norwegian FRAM 2014-15 ice drift from RV Polarstern on 2 August 2008.

Pacific Water outflow from the Arctic Ocean, modified by interaction with river runoff water over the upstream Canada Basin.

(ii) The Halocline layer centered at ~80 m (salinity of ~33) separates the Pacific-origin cold Halostad from the Polar Water, modified by interaction with warm Atlantic water outflow from the Arctic Ocean through Western Fram Strait. The upper boundary of the Atlantic water (T ~ 0°C) is recorded at ~170 m depth on the continental slope and ~30 m shallower over the adjoining shelf (Figure 2). This difference suggests that, as with the subsurface layer, the intermediate water over the shelf and continental slope is conditioned by different branches of the Atlantic water outflow from the Arctic Ocean.

(iii) The lateral shelf-slope interaction between on-shelf relatively warm Atlantic-modified Halocline water and off-shelf cold Polar Water gives rise to the intrusive interleaving observed over the Wandel Sea outer shelf (Figure 3).

(iv) At the base of the Halocline layer, cold and turbid water intrusions were recorded at the front of the tidewater glacier outlet. The temperature-salinity plots of the CTD profiles from this region show a mixing line that is deflected relative to the ambient water (Figure 3). Both features are likely conditioned by the ocean-glacier thermal interaction.

Ice Algae and Under-ice Algal Blooms

The concentration of chl a biomass during the spring bloom in Dease Strait was low compared to other regions of the Canadian Arctic Archipelago. This was also true for the amount of nitrogen (nitrate + nitrite), where concentrations were representative of nutrient deplete ice in Greenland Fjords (e.g. Mikkelson et al., 2008). Measurements of primary and community production were accomplished using a novel oxygen optode method that monitored the change in dissolved oxygen over time at a range of light

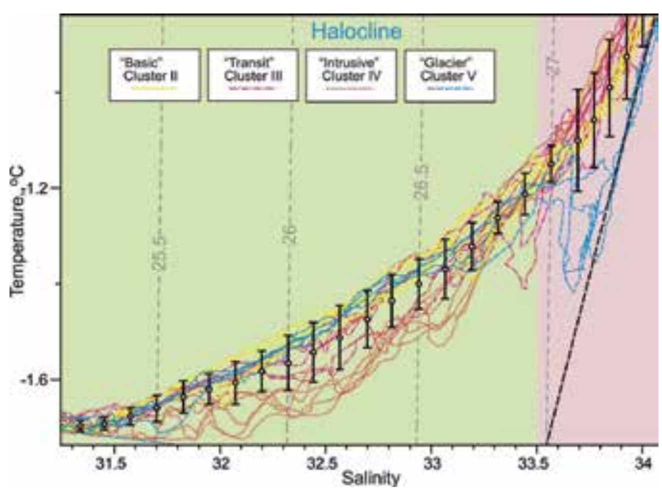

Figure 3. In situ temperature and salinity curves for the CTD profiles grouped into Clusters II–V. The mean TS characteristics ±1 standard deviation (white barred dots) are presented at isopycnal intervals of 0.1 kg m^{-3}.

intensities (0, 10, 22, 55 μmol m^{-2} s^{-1}). This method also permitted the calculation of photosynthesis-irradiance parameters that describe the photophysiology of algal cells to environmental conditions. We found that photosynthesis-irradiance parameters calculated from our optode method were comparable to result from traditional 14°C incubations (Figure 4) (Campbell et al., 2016). This represents a particularly important finding for Arctic research given the difficulties encountered with radioisotope use in remote field locations. Net community production in Dease Strait changed over the spring from, at times, net heterotrophic (CO_2 producing) to net autotrophic (CO_2 consuming). The composition of sea ice algae changed over the spring, where POC:Chl a increased under both thin or thick snow covers. The ratio of POC:Chl a along with POC:PON were both significantly greater under thin snow cover.

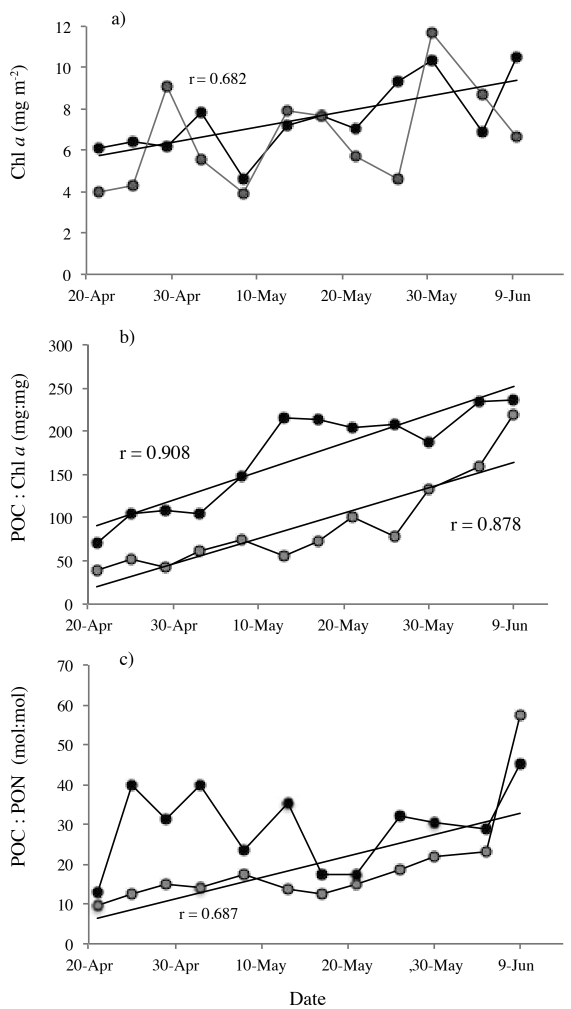

Figure 4. Seasonal changes in (a) bottom-ice chlorophyll a (chl a), (b) ratios of particulate organic carbon (POC) to chl a, and (c) POC to particulate organic nitrogen (PON), under thin (black) and thick (grey) snow covers. Significant (solid line) (p < 0.05) seasonal trends are also indicated, with associated correlation coefficients.

Near Davis Strait, offshore from the community of Qikiqtarjuak, Nunavut (67°29.23N, 63°38.00W) during the Green Edge project, in 2015, there was no significant difference of the ratios of photoprotective pigments between ice algae, sinking algae and phytoplankton until the snow melt period. At this time, a gradient of photoprotection was observed with higher ratios in the bottom of ice algae, followed by the phytoplankton at 0.5 m and 5 m. Contrariwise, in 2016 the bottom ice algae possessed a higher photosynthetic efficiency and lower saturation irradiance, which indicate a low photoacclimation. In opposition to ice algae, the photosynthetic efficiency of phytoplankton from 1.5 and 10 m was lower, while the light saturation was higher.

Concerning the *in situ* experiment, we obtained two under-ice blooms. One (5 m water) was dominated by the pennate diatoms, *Navicula* sp., while the other (under-ice water + ice algae) was dominated by *Cylindrotheca* sp. and *Nitzschia frigida* (Exp. 2: under-ice water). In both experiments, the growth of both under-ice blooms was limited by nitrate. However, the pattern of bacterial and primary production was different between both under-ice blooms.

DISCUSSION

Sea Ice Biogeochemical Cycling

In summer, the combination of both sea ice melt and the associated ice-edge bloom promote a strong undersaturation of the surface pCO_2^{sw} relative to atmospheric concentration. Regionally, the Coppermine River (in Coronation Gulf) likely support the mineralization of organic material delivered to the marine system which results in higher pCO_2^{sw}. By autumn, temperatures had decreased and sea ice was beginning to form and the pCO_2^{sw} was undersaturated throughout the CAA. However, despite the decreased in sea surface temperatures (SSTs), surface pCO_2^{sw} increased throughout our study region, except in Coronation Gulf, where the summer supersaturation had reversed to undersaturation. We attribute the increase in surface pCO_2^{sw} across most the eastern archipelago in part to the uptake of atmospheric CO_2 by air-sea exchange and to the deepening of the mixed-layer potentially bringing CO_2-rich waters to the surface. In Coronation Gulf, the seasonal reduction in discharge from the Coppermine River, associated with surface cooling was likely responsible for the observed decrease in pCO_2^{sw}.The general pCO_2^{sw} undersaturation during the summer-autumn 2011 throughout the CAA, resulted in an estimated net oceanic sink for atmospheric CO_2 averaging -11.4 mmol CO_2 m^{-2} d^{-1}, neglecting the possible roles of sea ice in the CO_2 exchange.

Ikaite concentrations measured with the DIC method yielded higher ikaite concentrations than the image analysis method in all sections in multi-year ice since very few crystals. Ikaite is not considered stable at temperatures greater than 4ºC (Dieckmann et al., 2008) and begins to dissolve immediately when it is warmed. Image analysis was completed in a 20˚C laboratory, so ikaite crystals that were smaller than approximately 5 µm may have dissolved before they could be photographed. Any crystals that are not photographed are not counted in concentration calculations. This could result in an underestimation of ikaite concentration when using image analysis.

As a result of the presence of large bubbles and higher air volume fraction measurements in sea ice we introduce new perspectives on processes regulating gas exchange at the ice-atmosphere interface, and note that the air volume fraction should be an important inclusion in parameterizations of sea ice permeability.

Sea Ice Physical Properties and Processes

Numerous studies have reported the possible influences of the Arctic sea ice loss on atmospheric temperature and circulation (Honda et al., 2009). However, it has been shown that the impact of autumn Arctic sea ice concentrations on atmospheric patterns in the following winter remains uncertain (Hopsch et al., 2012). Our result shows that there is a stronger relationship between summer sea surface temperature anomalies and winter circulation patterns, rather than a relationship with sea ice concentration.

The trends of atmospheric circulation and air temperature over the Arctic Ocean are correlated with the Arctic sea ice extent (Ogi and Rigor, 2013). Sea ice pack in the Hudson Bay recently began to break up earlier in spring. The trends in the breakup dates agreed with the temperature trends at the weather stations situated along Hudson Bay (Gagnon and Gough, 2005). These atmospheric circulation and air temperature trends controlled the sea ice extend trends in both Hudson Bay and the Arctic Ocean. As a result, the summer sea ice extent between Hudson Bay and the Arctic Ocean are strongly positively correlated.

Hydrodynamic of Arctic shelf seawater and fjords system

The study in Young Sound covers seasonal and spatial variability of hydrodynamics in an Arctic Fjord with shallow sill. Our study identified a tidally driven fjord-shelf exchange mechanism which created a salt flux estimated between 145 kg s^{-1} and 603 kg s^{-1}.

The stations taken on the Wandel Sea shelf and the Greenland slope farther to the east in May 2015 reveal advected water masses of at least two streams, one over the shelf, the other along the continental slope. The one over the slope has warm, saline Atlantic water (AW) lying below a deep, cold, less saline and fairly homogenous upper layer and low salinity surface water created by seasonal ice melt and heated by solar radiation. In the Nansen Basin this layer is homogenized by haline convection each winter (Rudels et al., 1994). The surface water found on the shelf has much colder and less saline AW than the AW across the slope. The AW characteristics here are similar to those observed at much larger depth in the Canada Basin, indicating AW that has circulated around the entire deep Arctic basins and now is returning towards Fram Strait. In the Canada Basin, the AW is covered by the halocline layer. It comprised both the Atlantic (S ~ 34) and Pacific derived water, especially the Pacific winter water, with S ~ 33.1, as well as other low salinity waters. These low salinity waters lie shallower than the sill depth of the Canadian Arctic Archipelago and can pass through the straits into Baffin Bay. This would cause the AW to rise in the water column and eventually be shallow enough to flow over deeper shelves like that of the Wandel Sea. Over the Wandel Sea shelf, the Pacific winter water, so distinct in the Canada Basin, seems to be either missing or only occupying a narrow depth range. Instead the coldest water is found in the Halostad with salinity around 31 instead of 33. The low salinity upper layer and the thick ice cover in winter preclude the local homogenization of the water column down to the Halostad. Thus, the Halostad must be advected from elsewhere. A conceivable scenario could be that most of the Pacific Water drains out of the Arctic Ocean through the Canadian Arctic Archipelago. This makes the AW ascend and it would allow water from the Polar Mixed Layer, of Atlantic or Pacific origin, in the Arctic Basin to replace the water leaving through the straits in the archipelago and penetrate onto the shelf, creating a different upper layer above the AW.

Ice Algae and Under-ice Algal Blooms

Ice algal productivity in Dease Strait was co-limited by light intensity and the availability of nitrogen. Light is commonly reported as a controlling factor of growth and productivity during the early phase of the ice algal bloom (Leu et al., 2015). Typically nutrients become limiting during phases of peak accumulation as a result of increased demand with algal uptake (Leu et al., 2015). However, we found evidence of significant nitrogen limitation throughout the bloom in our study. For example, highly elevated POC:PON ratios were documented during early to late spring. We attribute low concentrations of nitrogen in the water column and sea ice to a combination of: limited surface water exchanges with neighboring water bodies, late spring stratification of the water column and minimal (2 cm s^{-1}) mixing at the ice-ocean interface. Limited exchange of surface waters with other regions also results in an accumulation of fresh riverine inputs and ice melt in the region. This was reflected by low salinity at the ice interface (28) relative to typical salinities of Arctic surface water (Campbell et al., 2016).

Bacterial production in sea ice is typically associated with the accumulation of algae during the spring bloom, as the majority of dissolved carbon substrate available to the bacteria is released from algal cells (e.g. Søgaard et al., 2013). However, we document for the first time that this important role of sea ice algae in the microbial loop may be specific to particular size fractions of algae. This highlights an important area of future research when assessing the movement of organic carbon in sea ice.

The photoprotective capability of ice algae seems to be variable between years, thus we need to look into the environmental factors (ice and snow thicknesses, incident irradiance, nutrient, etc.) to better understand these difference. The variation of the ratios of photoprotection of sinking algae seems to be associated with their origin: bottom of sea ice (ice algae) or directly from the water column (phytoplankton). The taxonomy of sediment traps will allow us to confirm the origin of algae.

Altogether these data will improve climate change models with the addition of physiological photo-adaptations by ice algae and under-ice blooms. This will permit a better estimation of the primary production (CO_2 uptake) over spring in the Arctic, an important biological process in a world where global CO_2 emissions continue to increase.

CONCLUSIONS

Sea Ice Biogeochemical Cycling

Observations of pCO_2^{sw} in the CAA show that freshwater from sea ice melt and rivers affect the pCO_2^{sw} differently. The general pCO_2^{sw} undersaturation during the summer-autumn 2011 throughout the CAA, resulted in an estimated net oceanic sink for atmospheric CO_2 averaging -11.4 mmol CO_2 m^{-2} d^{-1} throughout the study period, neglecting the possible roles of sea ice in the CO_2 exchange.

Based on results from the past two field seasons, DIC analysis of filtered crystals is an effective way to quantify ikaite. It is a more precise method than image analysis and calculated concentrations agree using both techniques. The May 2016 field campaign at Cambridge Bay was intended to further test DIC analysis of filtered ikaite crystals as a quantification technique.

CT X-ray imaging may allow for visualizations of transport pathways of bubbles. This information is vital to the improvement of models involving transport of biochemical compounds and gas transfer between the ocean and the atmosphere in polar oceans.

Sea Ice Physical: Sea ice extent and Atmospheric analysis

We have provided evidence that both winter and summer atmospheric circulations controlled air temperatures and sea ice extent in Greenland. The cold winter of 2013-2014 over North America was correlated with sea surface temperature over the Barents Sea from summer to winter. The atmospheric circulation had a strong impact on summer sea ice extent of both Hudson Bay and the Arctic Ocean.

Hydrodynamic of Arctic shelf seawater and fjords system

Tidal pumping is a major source of the dense water that drives the fjord circulation during the ice covered period. The fjord circulation brings relatively warm water in contact with the sea ice and might explain the ice thickness patterns observed in many fjords with shallow sill around the Arctic, where similar circulation patterns may occur.

The lateral shelf-slope interaction between on-shelf relatively warm Atlantic-modified Halocline water and off-shelf cold Polar Water gives rise to the intrusive interleaving observed over the Wandel Sea outer shelf (Figure 3). The temperature-salinity plots of the CTD profiles from this region show a mixing line that is deflected relative to the ambient water (Figure 3). Both features are likely conditioned by the ocean-glacier thermal interaction.

Ice Algae and Under-ice Algal Blooms

Our study is an important step towards understanding the seasonal and spatial variability in sea ice productivity across the Arctic. The location of these measurements will contribute to the baseline of future studies in the area that are likely to occur with the development of the Canadian High Arctic Research Station (CHARS). Furthermore, we developed an effective method for monitoring production in sea ice, and document new findings in this field of research that include: the potential for heterotrophic conditions during the ice algal bloom, the importance of small (picoeukaryote) algae in the microbial loop, the contribution of taxonomic composition to primary production in sea ice. Our study improves also our knowledge of the physiological adaptation to light of ice algae and the under-ice blooms, two communities in perpetual co-existence. This time series over spring represents an additional dataset in a field rarely studied in the Arctic.

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UNDERSTANDING THE EFFECTS OF CLIMATE CHANGE AND INDUSTRIAL DEVELOPMENT ON CONTAMINANT PROCESSES AND EXPOSURE IN THE CANADIAN ARCTIC MARINE ECOSYSTEM: HOW CAN WE PREPARE?

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ABSTRACT

Recent studies have shown that climate change is already having significant impacts on many aspects of transport pathways, speciation, cycling and exposure of contaminants within Arctic ecosystems. For example, the extensive loss of sea-ice in the Arctic Ocean and the concurrent shift from greater proportions of perennial to annual types have been shown to promote changes in primary productivity, food web structure, mercury methylation and demethylation rates, and mercury distribution and transport across the ocean–sea ice atmosphere interface (bottom-up processes). Changes in animal social behavior associated with changing sea-ice regimes are now known to affect dietary exposure to contaminants (top-down processes). In addition to the climate effects on contaminant cycling and exposure in the Arctic, the changes currently underway in sea ice cover, and market pressures for new resources, have resulted in a significant increase in planned or prospective natural resource development. In particular, there has been a resurgence of interest from oil and natural gas companies in exploration and development licensing. Additionally, shipping traffic through the Canadian Arctic is predicted to increase with decreasing ice concentrations. The environmental issues surrounding oil spills in ice-covered waters; however, remain a key concern of all stakeholders.

The proposed study will provide valuable scientific information needed to support Arctic governments in their efforts to take remedial and preventive actions relating to contaminants and adverse effects of climate change and industrial development in the Arctic marine environment. It will help answer the question "How can we prepare?"

KEY MESSAGES

Persistent Organic Pollutants in Canadian Arctic Seawater

- Many of the persistent organic pollutants we detected in the Beaufort Sea have been banned by national and international regulators, including hexachlorocyclohexanes, chlordanes, DDTs and PCBs.
- Microplastic debris was identified in sediments collected at Frobisher Bay, near Iqaluit and in the Mackenzie Delta.

Mercury Fluctuations in Marine Mammals

- Mercury (Hg) isotope ratios are potentially useful to examine biological and environmental factors affecting the bioaccumulation of Hg in the Arctic marine environment.
- Measuring the mass-dependent (MDF) and mass-independent fractionation (MIF) of Hg stable isotopes in ringed seals should help us to develop an understanding of factors affecting year-to-year fluctuations in Hg concentrations in seal tissues.

Biogeochemical Cycling of Mercury in the Arctic Ocean and Hudson Bay

- The sub-surface enrichment of methylmercury (MHg) in Arctic seawater matches very well with the Pacific halocline waters, suggesting much of it could be due to transport. Demethylation of methylmercury in seawater occurs faster than methylation, and appears to be enhanced in the presence of particles.
- Concentrations of total (THg) and MHg in surface waters of lakes and rivers in the Nelson River Watershed (western Hudson Bay) are generally low. Efforts are being taken to obtain historical data from sediment cores to probe the influence of hydroelectric regulation.

- In the Thomsen River watershed (Banks Island) permafrost slumping has resulted in a release of a considerable amount of total mercury into the watershed.

Hydrocarbons in Western Hudson Bay Sediments

- Hydrocarbon profiles for surface sediments collected from Chesterfield Inlet, NU, indicate pyrogenic sources of hydrocarbons, while those in Wager Bay, NU, indicate mixed biogenic and pyrogenic sources.

Petroleum Hydrocarbons in Baffin Bay Sediment and Sea Stars

- Preliminary biota-sediment accumulation factors between sediment and sea stars in Baffin Bay indicate that location is a more important driving factor with respect to this variability, as opposed to species type.

Interactions between Oil and Sea Ice

- Corn oil has been verified as a suitable, non-toxic proxy for crude oil to use in oil in sea ice experiments.
- Oil has been observed to decrease sea-ice salinity and affect its properties related to radar detection.

OBJECTIVES

1. *Persistent Organic Pollutants in Canadian Arctic Seawater*

a. To measures levels of persistent organic pollutants (POPs) in Canadian arctic water;

b. To deploy passive water samplers in multiple locations in the Canadian Arctic;

c. To screen for new and emerging compounds of concern in the Canadian arctic water;

d. To screen for the occurrence of microplastics in arctic water and sediment.

2. *Mercury Fluctuations in Marine Mammals*

a. To determine whether there are changes in the mass-dependent (MDF) and mass-independent fractionation (MIF) of Hg stable isotopes (HgSI) in seal muscle among years and whether they are related to annual variations in total mercury concentrations (THg) and the number of ice-free days (and hence a change in light regime);

b. To determine whether changes in diet, as exemplified by stable isotope ratios of nitrogen and carbon ($\delta^{15}N$ and $\delta^{13}C$, respectively) and possibly fatty acid signatures, also change with annual variations in extent of ice cover and how these may affect Hg isotopic signatures;

c. To determine whether there are differences in the MDF and MIF of Hg stable isotopes in different tissues (muscle, liver, kidney, blubber) of ringed seals. Differences in isotopic fractionation may provide insights on relative demethylation rates of MHg rates among these tissues.

3. *Biogeochemical Cycling of Mercury in the Arctic Ocean and Hudson Bay*

a. To understand biogeochemical cycling of Hg, especially mercury methylation, in seawater and the sea ice environment in the Arctic Ocean including Hudson Bay.

4. *Hydrocarbons in Western Hudson Bay Sediments*

a. Provide baseline concentrations of hydrocarbons in surface sediments in western Hudson Bay;

b. Interpret sedimentary processes influencing contaminant distribution.

5. *Petroleum Hydrocarbons in Baffin Bay Sediment and Sea Stars*

a. Determine baseline concentrations of petroleum hydrocarbons in sediment and benthic organisms;

b. Compare bioaccumulation patterns among various sea star species.

6. *Interactions between Oil and Sea Ice*

a. To observe the partitioning behaviour of the crude oil mixture in the ice and water column to see which compounds have a greater tendency to penetrate farther into the ice, thereby potentially influencing its properties for active microwave remote sensing (e.g. detecting oil in sea ice).

KNOWLEDGE MOBILIZATION

- A total of 21 presentations were delivered at scientific conferences (e.g. Canadian Society of Chemistry Annual Conference, ArcticNet Annual Science Meeting, SETAC NA, the Brominated and other Flame Retardants workshop (BFR 2016), the Northern Contaminants Results Workshop).
- L. Jantunen presented results to the Nunavut Environmental Contaminants Committee (NECC) in Iqaluit and discussed how indigenous knowledge and capacity building can be incorporated into this project and how to best communicate our project and findings to northern communities.
- Along with two other researchers from the NCP, L. Jantunen will be visiting Nunavut Arctic College and giving a lecture and hands on demonstration of collection, processing and analysis of arctic air and water samples in February 2017. This is a follow up to previous visits in February 2014 and 2016.
- A project overview of the "Mercury fluctuations in marine mammals" was presented to the Inuvialuit Fisheries Joint Management Committee January 2016 (Ghemire et al. 2016).
- F. Wang delivered the Stairs Lectures in Chemistry at Trent University. One was a public lecture and the other a research seminar.
- F. Wang did two interviews with online and print media (UM Today, Trent University Daily News).
- M. Armah and A. Gaden provided preliminary data of Nunavut environmental monitoring projects to the NGMP secretariat.

INTRODUCTION

Persistent Organic Pollutants in Canadian Arctic Seawater

Since 2014, passive water samplers (PWS) have been deployed on moorings in the Beaufort Sea. In 2016, PWS were also deployed on moorings in the Davis Strait and near Cambridge Bay. The goal of this work is to develop a passive water monitoring network in the Canadian Arctic for Persistent Organic Pollutants and compounds of emerging concern as identified by the Chemical Management Plan and the Northern Contaminants Program (INAC). This network is part of a Global Network of passive water samplers called AQUA-GAPS (Lohmann et al., 2016). Our understanding of the contamination of arctic waters by persistent organic pollutants (POPs) is limited to sparse surface measurements. Levels of POPs in Arctic waters are at low concentrations (pg-ng/L) but will bioaccumulate in arctic biota to levels that are of concern especially when consumed by northerners. Instead of processing 100's of litres of water, PWS were deployed, accumulating contaminants from water at a known rate.

New to the project this year, we investigated microplastics in the arctic. Microplastic pollution has been found across the globe but with limited information from the polar regions. Although there is evidence of microplastics in the Arctic and Antarctic, little is understood about the sources, fate and extent of contamination. We investigate these questions by screening arctic sediment and water for the presence of plastic debris.

Mercury Fluctuations in Marine Mammals

Recent studies have shown that climate change is already having significant impacts on many aspects of transport pathways, speciation, cycling and exposure of contaminants within Arctic ecosystems. For example, Gaden et al. (2009) showed that Hg in ringed seals vary depending on the extent of sea-ice cover in the preceding winter. Recent work (Point et al. 2011) showed that Hg stable isotopic signatures (HgSI) in Arctic seabirds were also affected by sea-ice cover, which they attributed to changes in MHg photodegradation rates in the ecosystem. More recently, Masbou et al. (2016) reported similar findings on Hg isotopic fractionation in ringed seal tissues using archived samples collected from different coastal locations in Alaska. Building on these studies, we will more closely examine factors that may affect year to year variation in Hg accumulation in ringed seal tissues (muscle, liver, kidney, blubber) from Ulukhaktok, NWT including ice-related differences in light regime by examining changes in HgSI, variations in diet based on carbon and nitrogen stable isotopes, and fatty acid signatures. Our study design is more robust than that of Masbou et al (2016) as all seals were collected from the same location, a larger sample size (100-120 animals) with multiple tissues being examined.

Biogeochemical Cycling of Mercury in the Arctic Ocean and Hudson Bay

Evidence is now mounting that the highly variable Hg concentrations in Arctic marine mammals in recent decades are no longer a simple function of external, anthropogenic mercury emissions; instead, they are increasingly driven by climate-induced changes in post-depositional processes that control the transport, transformation, and biological uptake of stored mercury in the Arctic Ocean (AMAP, 2011; Wang et al., 2010). We have recently shown that the sea ice environment plays a major role in controlling the magnitude and timing of atmospheric mercury flux to the underlying marine ecosystem (Burt et al., 2013; Chaulk et al., 2011). We have also shown a profound production zone of MHg in sub-surface seawater in Beaufort Sea (Wang et al., 2012), and potential MHg production in the Arctic multi-year sea ice (Beattie et al., 2014). However, major uncertainties exist with respect to the net transport of atmospheric mercury to the ocean, the mechanism by which sea ice affects the net atmospheric transport of mercury, and the process responsible for methylmercury production in seawater and sea ice.

Hydrocarbons in Western Hudson Bay Sediments

Mining operations in Baker Lake, NU, have resulted in significant increases in ship traffic through Chesterfield Inlet, NU. Further north, Ukkusiksalik National Park, a relatively new Canadian Park, is poised for an increase in tourism and related maritime traffic. To brace for a future scenario of more frequent marine traffic in these areas, we set out to collect baseline contaminant data associated with oil and gas in the sediments in these regions.

Petroleum Hydrocarbons in Baffin Bay Sediment and Sea Stars

The most serious threat to marine ecosystems is an oil spill (Arctic Council 2009). Baffin Bay is increasingly at risk of petroleum hydrocarbon exposure, as shipping is an important economic activity in the region. To enhance our current understanding of the status of petroleum hydrocarbon in the Baffin Bay benthic marine ecosystem, we investigated contaminants in paired sediment and benthic invertebrate samples. Sea stars were chosen for the analysis because they comprise a majority of the biomass composition among eastern Canadian Arctic mega-benthic communities (Roy et al. 2014) and they exhibit a variety of trophic niches relating to sediment and sedimentation (e.g. Hobson et al. 2002).

Interactions between Oil and Sea Ice

Remote sensing systems have played an increasingly important role in locating and tracking oil spilled in the open ocean for remediation purposes. However, methods for specifically detecting oil in ice and snow are in the early stages of development and require further research as the presence of sea ice impedes detection. Due to the inhomogeneous nature of sea ice, often air, sediment, salt, and brine are incorporated into the material, greatly complicating the interactions between the oil and sea ice as well as the interactions of the remote sensing signal. However, it has been hypothesized that active microwave remote sensing has the potential for detecting oil in sea ice through the measurement of the normalized radar cross-section (NRCS) of the ice. The NRCS of sea ice depends on the roughness of the ice surface as well as the complex permittivity profile of the ice, which in turn depends on the ice temperature and bulk salinity profiles. In the event of an oil spill in the Arctic, it is speculated that the temperature and salinity properties will be influenced through the inclusion of oil in the sea ice and the subsequent evolution of the ice and oil through weathering processes (e.g. dissolution, evaporation, percolation and migration through brine channels and ice cracks) and interactions, thereby affecting the NRCS of the sea ice.

ACTIVITIES

Persistent Organic Pollutants in Canadian Arctic Seawater

- All passive samplers deployed in 2015 were retrieved and redeployed on the moorings, including additional samplers in the northern Davis Strait and near Cambridge Bay.
- PWS deployed in 2014-2016 were semipermeable membrane devices (SPMDs) consisting of low density polyethylene sleeves containing triolein. Two additional types of PWS were also deployed in 2016 consisting of polyethylene (PE) and polydimethylsiloxane (PDMS, silicon rubber) strips. Water grab samples were collected at the deployment depths (50 to 300m) via the Rosette to confirm concentrations. Target compounds include: organochlorine pesticides (OCPs), polychlorinated biphenyls (PCBs), current use pesticides (CUPs), flame retardants (FRs), polybrominated diphenyl ethers (PBDEs), novel-FRs: brominated and chlorinate (NFRs), organophosphate esters (OPEs) and neutral perfluorinated compounds (PFASs).
- Archived sediment samples taken in 2015 as part of ArcticNet were analyzed for the occurrence of microplastics. Additionally, filtered water from oblique and zooplankton nets were taken to determine the occurrence of microplastics in arctic waters.

Mercury Fluctuations in Marine Mammals

- Refined analytical procedures for Hg stable isotopic analysis and calculation of mass-dependent and mass-independent fractionation ($\delta^{202}Hg$, $\Delta^{199}Hg$ respectively).
- Completed THg and mercury isotopic analysis (HgSI) on 100 muscle samples obtained from the DFO tissue archive.
- Initiated statistical analysis of data, examining the effects of year, sex, age on THg and HgSI, and relationships between THg and HgSI.
- Initiated analysis of nitrogen and carbon ($\delta^{15}N$ and $\delta^{13}C$) in seal muscle samples.
- Completed analysis of fatty acids, THg and MHg in muscle, liver, kidney and blubber from a subset of seals (n=20) as the basis for a contaminant risk - nutritional benefits analysis for consumption of seal meat.
- Obtained samples of Arctic cod for analysis of THg, MHg, HgSI and $\delta^{15}N$ and $\delta^{13}C$ from Amundsen Gulf to estimate Hg biomagnification factors and compare isotopic signature with those in seal tissue.

Biogeochemical Cycling of Mercury in the Arctic Ocean and Hudson Bay

- Sampled the Nelson River watershed sampling for analysis and further development of a methylmercury mass budget.
- Completed the CCGS *Amundsen* incubation sample analysis from 2015.
- Sampled the Thomsen River (Banks Island) watershed for analysis and further development of a methylmercury mass budget.

- Collected environmental samples aboard the *Amundsen* (Leg 3a&b).
- Completed the incubation sample analysis from the 2016 *Amundsen* cruise.

Hydrocarbons in Western Hudson Bay Sediments

- Sediment cores from seven stations were collected aboard the RV *Naliajuk* in the vicinity of Chesterfield Inlet and Wager Bay, NU. Cores were sectioned, frozen and shipped to the Centre for Earth Observation Science (CEOS) for further processing and extracting for petroleum hydrocarbons.
- Polycyclic Aromatic Hydrocarbons (PAHs) and n-alkanes were quantified in PETRL (Petroleum Environmental Research Laboratory) at CEOS. Diagnostic ratios of fluoranthene:pyrene and indeno(123-c,d)pyrene:benzo(g/h/i)perylene determined source-specific profiles of the sediments, including petrogenic (crude oil, fuels), pyrogenic (incinerated fossil fuels, wood, coal) and biogenic (produced by plants) contributions.

Petroleum Hydrocarbons in Baffin Bay Sediment and Sea Stars

- With the new enhancements made to PETRL the previous year (LECO Pegasus gas chromatographer with a high resolution time of flight mass spectrometer, gel permeation chromatographic system), we were able to analyze previously collected samples (2013-2015) for petroleum hydrocarbons. Additional data including stable isotope ratios of nitrogen and carbon and lipid/ total organic carbon content were collected to aid with the analysis.

Interactions between Oil and Sea Ice

- Conducted an experiment with several uncontaminated and oil-contaminated (corn and crude oil) ice cores in an artificial oil-in-ice mesocosm in a cold room at CEOS. Bulk salinity and temperature profiles of the ice were produced with and without the presence of oil.
- A second trial of the oil in sea ice experiment is scheduled for Jan-Feb (2017), this time using optical sensors from above and below the sea ice to measure the incident, reflected, and transmitted light to monitor its effect, if any, on the crude oil composition.

RESULTS

Persistent Organic Pollutants in Canadian Arctic Seawater

All PWS cages deployed were retrieved, biofouling was present but easily removed. The iodized aluminum cages showed no breakdown from seawater exposure but damaged easily during deployment and retrieval. Pesticides were easily detected in the SPMDs and in 200 L of seawater. PCBs and PBDEs were easily detected in the SPMDs but were below the detection limits in 200 L of seawater. Organophosphate esters FRs were not found in the SPMDs but they were very detectable in 4 L of seawater. OPEs were quite soluble thus not effectively collected by this type of sampler.

Benthic sediment samples were collected in the summer of 2015 from all regions of the Canadian

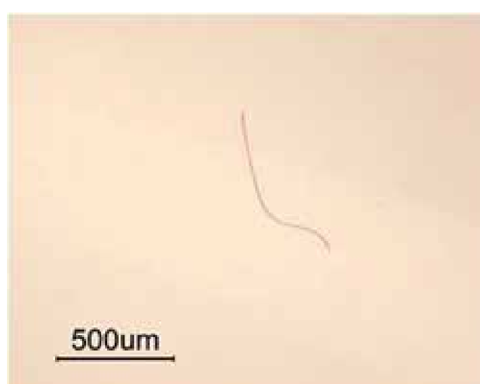

Figure 1. Fiber from a sediment sample taken in Frobisher Bay.

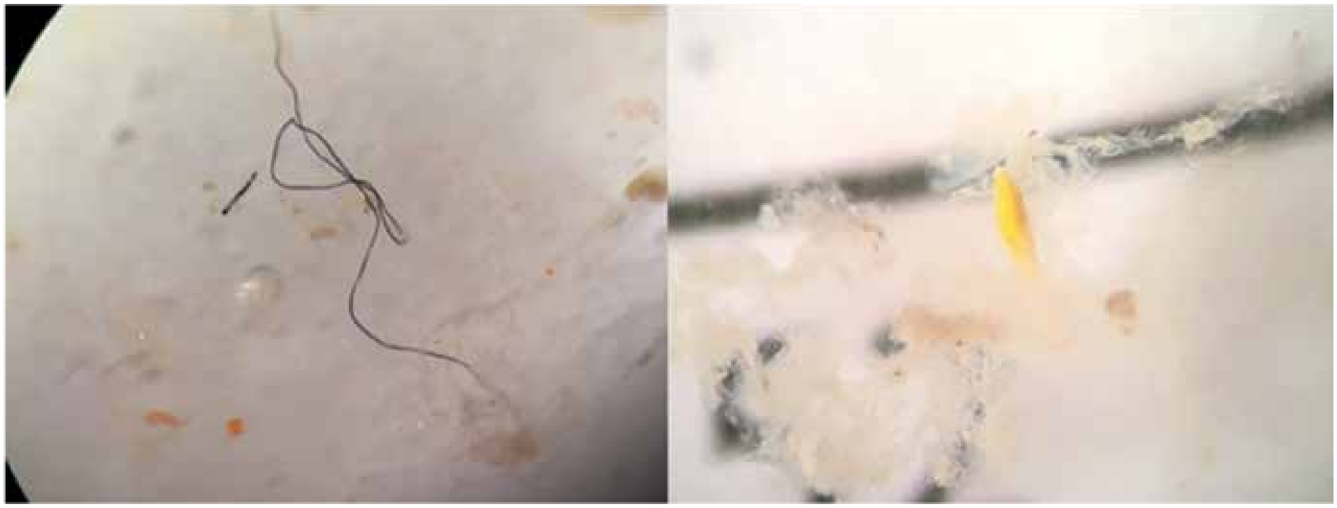

Figure 2. Fibers and chunks found in water samples from the Beaufort Sea.

Archipelago as a part of ArcticNet. The extra samples were archived and samples from Frobisher Bay, near Iqaluit and in the Mackenzie Delta were sent for microplastic analysis. Samples were ~100 mL of sediment, containing the top 5 cm of sediment from a box corer. Microplastic debris was identified in both samples, containing 11 fibers. All microplastics were very small fibers, <1 mm in length. Most of the fibers were blue, and a few were red and one black (Figure 1).

Five filtered water samples from zooplankton nets (200 µm) were collected in the summer of 2016 to screen for microplastics. Two types of samples were collected: oblique tows and vertical bottom to top nets. Evidence of microplastic was found in all five samples, consisting of both fragments and/or fibers. Across all five samples, the quantity of microfibers ranged from 22–105 and fragments from 0–15. See Figure 2 for an example of each particle type, fiber and fragment. Although future analyses will use Raman to verify that each particle is indeed microplastic, preliminary data suggests this material does contaminate the Canadian Arctic. The majority of microplastic observed was fibers, consistent with ocean water sampled from the Greenland Sea, which found that 97% of microplastics were fibers (Amelineau et al., 2016).

Mercury Fluctuations in Marine Mammals

THg and HgSI were determined in muscle tissue of 100 seals (20 seals from each of five different years) from Ulukhaktok, NWT using cold vapor atomic fluorescence spectrometry (CVAFS) and multicollector ICP/MS, respectively. While statistical analysis of these data is incomplete it does appear as if THg was significantly higher in years with longer periods of ice cover compared to years with less cover. Results of the HgSI analysis does show that significant mass dependent (δ^{202}Hg) and independent (Δ^{199}Hg and Δ^{201}Hg) fractionation is evident in seal muscle and may be related, in part, to the age of seals. More detailed statistical analysis is needed to address the effects of age, sex and year on the HgSI data.

We also examined concentrations of THg and MHg in muscle, kidney, liver and blubber from a subset of the same ringed seals (n=20), along with concentrations of n3-polyunstaruated fatty acids (PUFAs): eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). We have used these data to conduct a risk benefit analysis for consumption of seal tissues, taking into account the adverse effects of Hg and MHg contrasted with the health benefits of fatty acids.

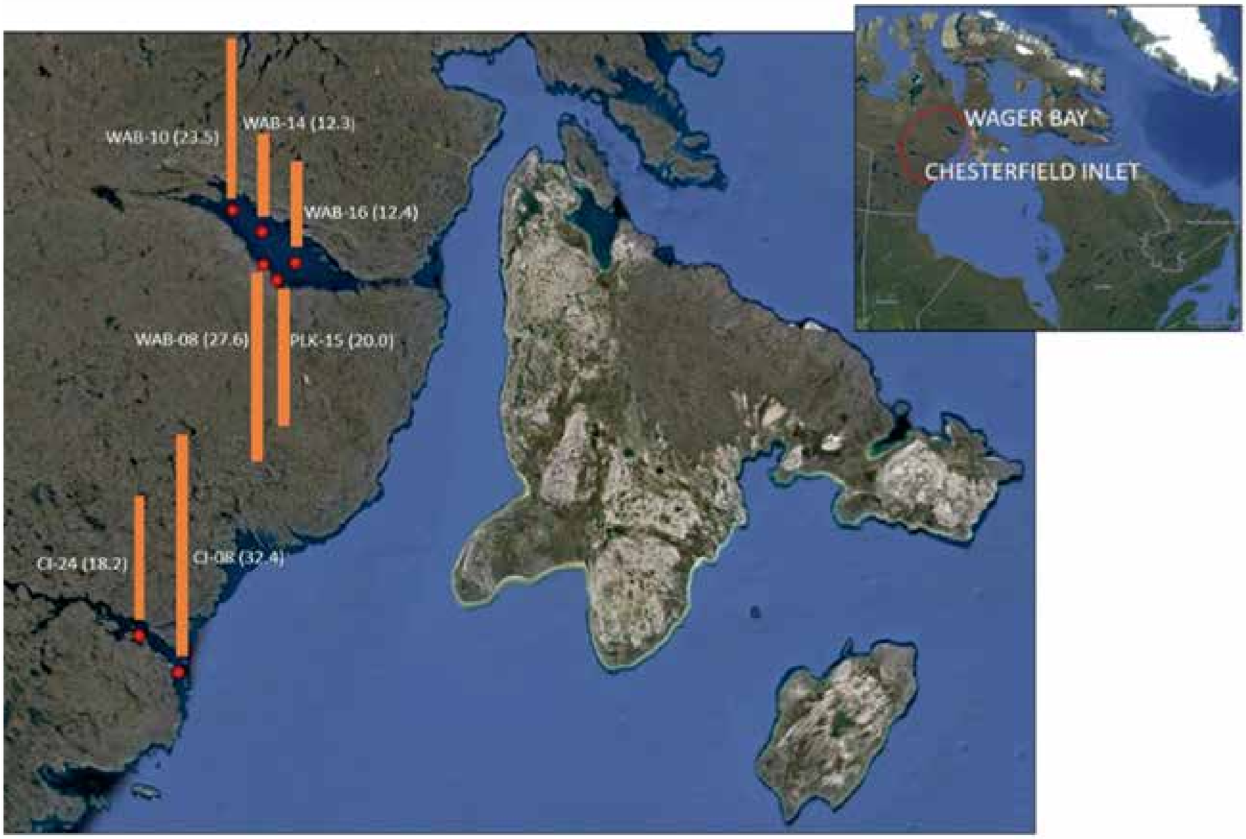

Figure 3. Average total PAH concentrations (ng/g dry weight) for the surface 2 cm at sample locations in western Hudson Bay.

Biogeochemical Cycling of Mercury in the Arctic Ocean and Hudson Bay

High resolution profiling of MHg revealed that the major sub-surface peak in MHg in the Canadian Arctic was primarily associated with the Pacific halocline waters. Elevated MHg concentrations were also found at depth of subsurface chlorophyll maximum and in a few locations in the surface water. Incubation experiments showed the occurrence of methylation and demethylation in seawater samples taken from different sites, but the demethylation rates were always much higher than methylation rates. No significant enhancement of methylation was found in the unfiltered waters compared to the filtered ones. Concentrations of Hg and MHg in four lakes in the Nelson River systems of the Hudson Bay watershed were generally low. THg concentration in the Thomsen River was higher at sites downstream of permafrost slumping.

Hydrocarbons in Western Hudson Bay Sediments

Preliminary results reveal the average concentrations of total PAHs were within the range of 12.3-32.4 ng/g in surface sediment (Figure 3). The diagnostic PAH ratios indicated that Chesterfield Inlet sediments depicted pyrogenic sources. At Wager Bay, sediment PAH ratios depicted mixed biogenic and pyrogenic sources across sediment samples.

Petroleum Hydrocarbons in Baffin Bay Sediment and Sea Stars

Preliminary analysis indicated the total PAHs in surface sediment averaged 113 ng/g (range of 19-255 ng/g). East Baffin Bay had significantly higher concentrations of high molecular weight PAHs than in the North Water Polynya. Total n-alkanes

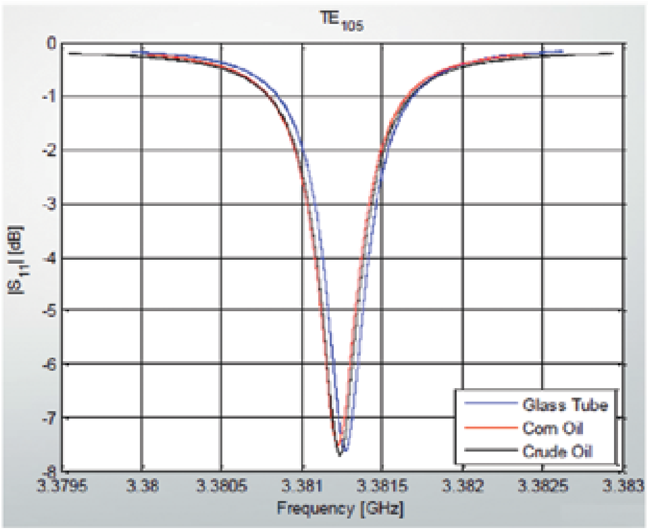

Figure 4. TE105 permittivity measurements of corn oil, crude oil, and a glass tube with cavity over coupling for all three cases using a resonant perturbation method (Chen et al. 2004). Data and figure provided by Thomas Neusitzer (University of Manitoba).

were within 249-5629 ng/g. In sea stars the total PAHs averaged 75 ng/g (range of 6-257 ng/g, with one sample in East Baffin Bay at 497 ng/g). Chrysene/triphenylene was significantly higher in *Ctenodiscus crispatus* than *Gorgonocephalus* sp. Lower to mid-molecular weight PAHs were higher in biota compared to their paired sediment samples across all locations and species. PAHs heavier than pyrene (>202 g/mol) were generally more concentrated in the sediment relative to paired biota.

Interactions between Oil and Sea Ice

Corn oil was determined to be a suitable proxy for crude oil. Both had reasonably similar permittivity (Figure 4) and similar average density and overall affinity to water. Corn oil is also a safer, non-toxic alternative to test how sea ice evolves in its presence. Through our oil in sea ice experiments, we have found that oil migrates up through the ice due to its buoyancy, displacing some of the brine. The decrease in brine from within the brine channels causes a drop in sea-ice salinity, thereby affecting the sea-ice's complex permittivity and other properties affecting detection by radar.

DISCUSSION

Persistent Organic Pollutants in Canadian Arctic Seawater

Many of the POPs we detected in the Beaufort Sea have been banned by national and international regulators. This includes several pesticides (hexachlorocyclohexanes (HCHs), chlordanes and DDTs) and PCBs (Hung et al., 2010; Jantunen et al., 2015; Su et al., 2008; Ryan et al., 2013; Riget et al. 2010). The same trends are seen for banned flame retardants (for example PBDEs), fluorinated compounds (for example PFOS) and an organophosphate flame retardant banned in Europe is also declining in Canadian arctic air. Climate change may be disrupting these declines due to changes in water flows, ice cover and surface water temperatures so continued monitoring of these compounds is important. Levels of pollutants still being applied or used in commerce are remaining steady or are increasing in the Canadian arctic environment, including current use pesticides in air and water (Jantunen et al., 2015), some organophosphate flame retardants in air (Suhring et al., 2016) and hexabromocyclododecane (HBCDD), a PBDE replacement chemical, seem to be increasing in arctic char, lake trout, ringed seals and beluga (CACAR III, 2013). Monitoring of currently used industrial chemicals, flame retardants and pesticides in the Canadian arctic is crucial to assess whether these compounds pose a risk to Northerners and to develop a case for national and international regulations before they become a health hazard in the arctic.

Microplastics have been identified as a global pollutant of concern that is capable of long-range transport and can cause adverse effects in wildlife; however, there is very little Arctic data. Consequently, it has been identified as a Chemical of Emerging Arctic Concern by AMAP and the Northern Contaminants Program (INAC).

Mercury Fluctuations in Marine Mammals

To date, our results are consistent with the finding of Gaden et al. (2009) that THg tends to be lower in years with less ice cover, but it is too early to tell whether HgSI signatures in our study are also influenced by the extent of ice cover or other variables.

Biogeochemical Cycling of Mercury in the Arctic Ocean and Hudson Bay

In the 2015 study we noticed "abnormally" high THg in surface seawater in Baffin Bay, which could have been indicated of glacier melt influence. Confirmation of this was not successful in 2016 due to 1) changes in the cruise plan and 2) cross-contamination in the rosette sampling area due to the modifications done to the Amundsen in 2015. The major sub-surface peak in MHg in the Canadian Arctic is most likely transported from the Pacific waters, suggesting the existence of Hg methylation hotspots in the Pacific waters and its influence on the Arctic. The surface or near-surface enrichment in MHg suggests that there might be another MHg source in surface seawaters, which is most likely related to biological activities, and/or that photodemethylation in the surface ocean might not occur as fast as we previously thought. We have also observed that particulate matter appears to play an important role in MHg demethylation, and permafrost slumping increases Hg loading to northern rivers.

Hydrocarbons in Western Hudson Bay Sediments

Results imply that fossil fuel sources of hydrocarbon contaminants are more prevalent at Chesterfield Inlet than Wager Bay. This may be a result of higher volumes of traffic through Chesterfield Inlet (Andrews et al. 2016), which we will explore by analyzing hydrocarbon concentrations further down the sediment cores (e.g. older sections). Future work includes radioisotope analysis of lead and cesium to date the cores, and extending the analysis to include n-alkanes.

Petroleum Hydrocarbons in Baffin Bay Sediment and Sea Stars

Hydrocarbon concentrations in sediment were below the marine Interim Sediment Quality Guidelines and Probable Effects Levels for biota (CCME 2001). Bioaccumulation of contaminants from sediment to sea star appeared relevant at some stations in the North Water Polynya and Lancaster Sound, whereas other locations in Baffin Bay did not show evidence of bioaccumulation.

Interactions between Oil and Sea Ice

(Research pending)

CONCLUSION

Persistent Organic Pollutants in Canadian Arctic Seawater

Passive water sampling is a very effective way to estimate levels of low level contaminants in arctic water. This method is also a very cost effective way of sampling spatially across the Canadian arctic. New PWS devices for more soluble compounds are being assessed for deployment in 2017. Although there is now copious information regarding global microplastics contamination, there is limited information available for Canadian regions, particularly for Canadian Arctic regions.

Biogeochemical Cycling of Mercury in the Arctic Ocean and Hudson Bay

We have made major progress in understanding the source and fate of methylmercury in the Canadian Arctic seawater. Efforts are now being directed toward the development of a mass budget of methylmercury in both the High Arctic and Hudson Bay.

Remaining sub-projects

The analyses are ongoing and we look forward to completing the investigations and presenting their conclusion over the next year.

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ARC3BIO (MARINE BIODIVERSITY, BIOLOGICAL PRODUCTIVITY AND BIOGEOCHEMISTRY IN THE CHANGING CANADIAN ARCTIC)

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ABSTRACT

Arctic marine ecosystems provide numerous benefits and services of economic, societal and ecological value, including the provision of food resources, the conservation of biodiversity, carbon storage and nutrient recycling, among others. The Arc3Bio project combines the multidisciplinary skills of several experts to evaluate how climate variability and change, as well as direct human influence, affect the sensitivity and resilience of ecosystem functions and services at a variety of scales. Addressing different scales is necessary because the Arctic has strong connections with peripheral oceans and rivers. Variability and change at the regional scale, which is the focus of ArcticNet's Integrated Regional Impact Studies, can only be understood if external forcing at the boundaries is taken into account, and if the cumulative impacts of smaller-scale processes that shape biodiversity and biogeochemistry in different key areas are known. To do so we use an innovative combination of complementary approaches based on direct measurements from the CCGS *Amundsen* and other ships, remote observations of ocean color by orbiting satellites, and controlled experiments with samples from the water column and the seafloor. We pay special attention to the impact of changing light conditions and nutrient supply (especially nitrogen) on biological productivity and the contribution of different types of micro-algae that can be viewed as "good or bad" for the sustenance of zooplankton and the herbivorous food web. We also investigate how changing contributions of ice algae and phytoplankton to total primary production are likely to affect the benthic organisms living on the sea floor. Finally, coupled physical-biological numerical models are implemented to generate plausible futures for the productivity and structure of the lower marine food web, using climate projections made by Ouranos for 2025, 2050 and 2100. The results of our work is communicated though various means to stakeholders and communities (e.g. Regional Impact Assessment reports), the general public and the broader science community.

KEY MESSAGES

Treated in detail in the Results/Discussion section:

- A chronic deficiency of nitrate in the stratified surface waters flowing from the high Arctic into Baffin Bay explains why the Canadian sector is much less productive than the Greenland sector. This deficiency shapes the regional patterns of food web productivity across the Canadian Arctic.
- We found evidence that seasonal nitrate consumption by phytoplankton in the Canadian sector of Baffin Bay begins under the sea ice. This may explain why satellite-based estimates of productivity (this method does not detect under-ice chlorophyll and is susceptible to errors caused by the complex optical conditions prevailing at ice edges) seem to severely underestimate productivity in the Canadian sector of Baffin Bay.
- A novel dataset on the anisotropy of light reflectance by snow and ice offers a promising means to improve remote-sensing estimates of primary productivity near ice edges, where a large fraction of annual primary production is thought to occur in the Arctic Ocean.
- The regional differences observed in the resilience of the benthic communities in the Canadian Arctic imply that benthic trophic structure in the Amundsen Gulf is more sensitive to natural or anthropogenic disturbances than in the Canadian Archipelago and the North Water polynya. Results also showed that ice algae remain the primary source of carbon for benthic food webs.
- The Arctic macroinfauna exhibits considerable dietary flexibility, thriving on a variety of food sources. By virtue of this flexibility, Arctic benthic communities will possibly benefit from expected increases in pelagic primary production irrespective of the shift in food supply from ice algae to phytoplankton.
- Intense blooms of the prymnesiophyte *Phaeocystis pouchetii* can occur during summer in Labrador

fjords. This switch from palatable diatoms to a species often regarded as a nuisance in northern seas possibly has negative consequences for the food web when it occurs.

- We partly elucidated the mystery of dark winter survival of the pelagic ecosystem. A combination of *Micromonas* being relatively less able to maintain activity under dark winter conditions and viral suppression of *Micromonas* may have contributed to the success of *Bathycoccus* in the Amundsen Gulf during winter. This changes the paradigm that Micromonas dominates offshore assemblages throughout the year.

Not treated in detail in the Results/Discussion section (lack of space):

- Although size fractionated DNA surveys consistently report Dinophyceae in the picoplankton, a probability analysis concluded that these reads are most likely distinct life stages of known larger species and not new species (Lovejoy; HQP Onda). Issues of this type may affect the accuracy of biodiversity estimates.
- Infections by chytrid fungi were identified as an underestimated source of phytoplankton mortality, which modifies our understanding of algal ecology and fluxes of carbon and nutrients in surface Arctic waters (Lovejoy, HQP Comeau).
- The species composition of diatoms in western and eastern Baffin Bay (North Water) differs during summer, despite similar conditions of nutrients, chlorophyll biomass and temperature in the upper mixed layer. Communities of the subsurface chlorophyll maximum were dominated by *Pseudo-nitzchia* spp. near Greenland, while the *Chaetoceros gelidus* dominated near Canada (Lovejoy; HQP Joli).
- In contrast to nanophytoplankton (2-20 μm), the production of picophytoplankton (≤2 μm) was stimulated by decreasing pH during an incubation experiment conducted in Baffin Bay during summer, suggesting a possible future shift in food web structure and function with ongoing ocean acidification (Tremblay, Lovejoy; HQP Husscherr).
- *In situ* observations in Baffin Bay showed that the filamentous ice algae *Melosira arctica* does not sink right away upon being flushed or detached from the ice, contrasting with previous indications that it can also sink in a non-deteriorated state to bottom depths exceeding 4000 m in the central Arctic. This observation will inform models aiming to reproduce the sedimentation of particulate organic matter (Dumont; HQP Gremion).
- A mechanistic parameterization of the diurnal vertical migration (DVM) of zooplankton has been implemented in a coupled physical-biogeochemical model to study the associated impact on primary production and vertical carbon fluxes versus a model without DVM. Results obtained in a coastal oligotrophic environment show a strong decoupling between primary producer and grazers, a doubling of primary productivity and significantly increased organic matter fluxes toward the benthos (Dumont, Maps; HQP Nocera).
- The phenology of the phytoplankton bloom in the North Water is influenced by sea surface temperature, cloud fraction, wind stress and sea-ice concentration. Phytoplankton blooms last longer during years characterized by a longer open-water period and are shorter during those characterized by greater sea-ice coverage (Bélanger, Tremblay; HQP Marchese).
- Substantial drops in the magnitude of the phytoplankton bloom in the North Water were observed (sattelite-based) for the period 1998-2014), suggesting that this polynya may no longer act as a productive regional oasis supporting thriving populations of zooplankton and top predators (Bélanger, Tremblay; HQP Marchese).
- The satellite-based decrease of productivity in the North Water was corroborated with in-situ data obtained with CCGS *Amundsen* for the

fall, which showed a sharp, multi-year decline in centric diatom abundance as well as in the biomass and production of phytoplankton in northern Baffin Bay. These modifications were associated with a change in the seasonal timing of productivity and linked to alterations of sea-ice dynamics, freshwater input and vertical stratification (Gosselin, Tremblay, Bélanger; HQP Blais).

- Meanwhile, the relative abundance of diatoms in the southeast Beaufort Sea increased from 2% to 37%, accompanied by a doubling in the abundance of photosynthetic picoeukaryotes. These changes were correlated to an increase in the duration of the open-water period, which increased over the time series (Gosselin, Tremblay, Bélanger; HQP Blais).
- Our ability to detect phytoplankton functional types (PFTs) from space is limited by the spectral resolution of currently available multispectral ocean color sensors. Preliminary results showed distinct features in the reflectance spectra that are likely related to pigment compositions and to a certain extent, PFTs (Bélanger).
- In northern Labrador fjords, the species richness of protists (maximum of 201 taxonomic entries, 72 genera and 131 species identified) during early fall was twice as high as in summer, suggesting that the seasonal timing of biodiversity assessments for planktonic organisms may strongly affect the outcome (Gosselin; HQP Simo-Matchim).
- In summer, the algal community of melt ponds on the ice is dominated by chrysophytes, prasinophytes, prymnesiophytes or chlorophytes. These algae have efficient photoprotective mechanisms to prevent damage caused by sunlight, allowing them to maintain a high photosynthetic performance, despite low ambient nutrient concentrations (Gosselin, HQP Charette).

OBJECTIVES

1. To extend time-series of observations beyond the decadal time scale to better constrain the physical drivers of variability and change in primary production and different functional types of phytoplankton, ensuring that long-term ArcticNet time series yield their full benefits (ArcTrends);
2. To augment our quantitative understanding of nutrient supply (nitrogen in particular) and cycling in the water column and the benthos and their cumulative impacts on the biological productivity of waters flowing through the Canadian Archipelago, from the Beaufort Sea to the Labrador Sea (NitrArc); and
3. To advance biodiversity surveys of planktonic microbes and benthic communities and elucidate linkages between this diversity, biological productivity and ecosystem functions (DiveArc).

KNOWLEDGE MOBILIZATION

- Wide dissemination of results to the scientific communities, public, partners and stakeholders in high-ranking articles in preparation (8), submitted (15), accepted and/or published (18), invited talks (7), oral presentations (23), poster presentations (18), MSc (2) and PhD theses (2).
- Arc3Bio scientists who were present onboard during the Schools On Board Program provided talks and scientific demonstrations to the students.
- Our NIs and HQP presented their results at numerous national and international conferences: 12th ArcticNet Annual Scientific Meeting (Winnipeg, Canada), 15th General Meeting of Québec-Océan (Rimouski, Canada), GreenEdge Meeting (Nice, France), Gordon Research Conference (Ventura, USA), ALSO Aquatic Sciences Meeting (Honolulu, USA), European Geosciences Union General

Assembly (Vienna, Austria), Annual Science Conference of the International Council for the Exploration of the Sea (Riga, Latvia), Ocean Optics XXI and ESA Living Planet Symposium (Prague, Czech Republic), AGU Fall Meeting (San Francisco, California, USA), International Diatom Symposium (Québec, Canada), Goldschmidt 2016 conference (Yokohama, Japan), International Diatom Symposium (Québec, Canada), ISME Congress (Montréal, Canada), Arctic Frontiers (Tromso, Norway).

- We exchanged data, presented results and discussed during several workshops: NETCARE workshop 2016 (University of Toronto, Toronto, Canada), NETCARE workshop on the impact of Arctic DMS emissions on future climate (Institute of Ocean Sciences, Department of Fisheries and Oceans, Sidney, Canada), Sea Ice Biota workshop (University of Manitoba, Winnipeg, Canada), 2016 Amundsen Data Workshop (University of Toronto, Toronto, Canada), Geotraces Data Workshop (RBC Convention Center, Winnipeg, Canada), Kitikmeot Region Science Group Workshop (IOS, Sidney, Canada).
- Invited presentations: V. Carrier, N. Joli, D. Onda, C. Lovejoy and M. Thaler at the ISME Congress (August 2016, Montréal, Canada), N. Schiffrine at the International Diatom Symposium (August 2016, Québec, Canada), P. Archambault, A. Mäkelä and C. Nozais at the Oceanlab Arctic workshop (August 2016, Aberdeen, UK), N. Friscourt at the Annual Science Conference of the International Council for the Exploration of the Sea (September 2016, Riga, Latvia), D. Benkort, J. Charette, C. Dufresne, V. Galindo, D. Kalenitchenko and B. Saint-Béat, and at the 12th ArcticNet ASM (December 2016, Winnipeg, Canada), C. Lovejoy at Kitikmeot Region Science Group Workshop (Sidney, Canada), M. Gosselin during the visit of the French delegation Ocean+ (Rimouski, Canada), C. Dufresne and J.E. Tremblay at the ALSO Aquatic Sciences Meeting (March 2017, Honolulu, USA), S. Bélanger at the Journée d'Echanges ScienTifiques (Arcachon, France), D. Dumont at the Polar Marine Science, Gordon Research Conference (March 2017, Ventura, USA).
- Rewarded presentations: N. Friscourt; Best early career presentation at the Annual Science Conference of the International Council for the Exploration of the Sea (Riga, Latvia), N. Schiffrine; Second best oral presentation at the International Diatom Symposium (Québec, Canada).

INTRODUCTION

At the base of the food web, the photosynthetic primary production (PP) of organic matter (OM) by ice algae and different functional types of phytoplankton (PFTs) responds rapidly to changes in the availability of light, nutrients and other growth factors. This response conditions the productivity of harvestable resources since the intensity of PP by different PFTs sets an upper limit to the quantity of OM available to feed consumers higher up the food web (e.g. Bessière et al. 2007, Chassot et al. 2007). In parallel, the contraction of frozen habitats directly challenges organisms that depend on sea ice for nutrition, refuge or reproduction. Climate-driven decreases in the size and range of their populations along with invasions by temperate species will reshape biodiversity and ecological interactions, with effects rippling up and down the food web.

When a portion of algal biomass and derived detritus sinks beneath the surface, carbon atoms formerly bound in atmospheric CO_2 are transported downward. Variable proportions of this carbon are stored in deep waters, consumed by the benthic fauna or consigned to the sediment. The size and efficiency of this "biological CO_2 pump" depends on several factors (e.g., intensity of PP and dominance by different PFTs, community respiration, pH) that respond to the changing environment (e.g. Sabine and Tanhua 2010). The OM synthesized by algae and transiting through the food web must ultimately be decomposed and re-circulated to keep the finite reservoir of nutrients available.

Altered rates and pathways of nutrient cycling by pelagic and benthic microbes and consumers can therefore have a large cumulative impact on PP in the Arctic as well as in the 'downstream' subarctic regions it affects through the large-scale ocean circulation.

The present document reports on this year's progress in filling the major knowledge gaps identified in our initial proposal. These gaps are addressed through three interconnected workpackages focusing on the assessment and prediction of variability and change (ArcTrends) as it relates to alterations of the supply of nutrients and nitrogen in particular (NitrArc), and the diversity of species, communities and functions in the lower pealgic and benthic food webs (DiveArc). This year's focus was on the eastern Canadian Arctic.

ACTIVITIES

HQP training

- Six new PhD students were recruited (I. Deschepper, L. Jacquemot, M. PierreJean, L. Barbedo de Freitas, V. Marmillot and J. Lee; started in Spring 2016). Three of those have already and successfully passed their doctoral exam and will be presenting their PhD project soon.
- One PhD student finished her thesis and graduated (A. Simo-Matchim) and one PhD student will hand in her dissertation soon (A. Mäkelä).
- Three MSc students handed in the initial version of their dissertations (N. Friscourt, I. Courchesne and J. Charette).
- Two new MSc students were recruited (G. Filteau and A. Boivin-Rioux; started in Spring 2016).
- One undergrad student (S. Guérin) investigated the influence of environmental factors on the dynamics of bottom ice algae and under-ice phytoplankton near Qikiqtarjuak (Davis Strait).
- Trainees onboard the 2016 *Amundsen* expedition (M. Pelletier-Rousseau and N. Pelletier).

Sampling expeditions (national and international)

- Participation to the joint ArcticNet/GreenEdge/NETCARE expedition of CCGS *Amundsen* from June to October 2016 (J.E. Tremblay, D. Dumont, D. Kalenitchenko, M. Blais, J. Charette, G. Deslongchamps, J. Gagnon, G. Filteau, V. Marmillot, N. Pelletier, K. Chalut, G. Bravo, C. Nozais, C. Goyens, L. Barbedo de Freitas, J. Charette, M. Blais, A. Boivin-Rioux, M. Pelletier-Rousseau and P. Larouche).
- J.E. Tremblay (Leg 1b) and C. Nozais (Leg 2a) were chief scientists onboard the *Amundsen*.
- Participation to the BIO-DFO expedition of CCGS *Hudson* in the Labrador Sea in collaboration with VITALS during May 2016 (S. Bélanger, I. Courchesne, G. Deslongchamps, A. Théberge and L. Barbedo de Freitas).
- Participation to the GreenEdge ice camp (Qikiqtarjuaq, Nunavut) from March to June 2016 (P. Coupel, D. Dumont) in collaboration with A. Vladoiu (LOCEAN, Paris), C. Sévigny (ISMER-UQAR), G. Bécu (Takuvik, U. Laval) and P. Raimbault (MIO, France).
- Participation to the expedition of CCGS *Louis St Laurent* in the Canada Basin and the Amundsen Gulf (A. Monier).
- Participation to the expedition of CCGS *Des Groseillers* in Hudson Bay (J. Lee and S. Blondeau) from September to October 2016, as part of BaySys/ArcticNet collaboration.
- Participation to winter field expeditions in Churchill (G. Deslongchamps) and the Nelson River as part of the BaySys/ArcticNet collaboration (G. Deslongchamps).
- Invited participation (P. Archambault) to the Antarctica Circumnavigation Expedition on board the A. Tryoshnikov to study changes that occurred following the 2010 calving in the Mertz glacier region, East Antarctica (January 2017).

- Invited participation (L. de Montety) to a survey in South-West Greenland to collect benthic samples (June 2016) and North-West Greenland (September 2016).

Research progress and developments

- Archambault's team is processing samples of megafauna, sediments and particulate organic matter for bulk stable isotope ($\delta^{13}C$ and $\delta^{15}N$) analysis and samples of megafauna for compound specific isotope analysis.
- Bélanger's team is processing optical measurements (AOPs and IOPs) collected during the joint Arcticnet/Greenedge expedition and the VITALS cruise.
- Gosselin's team completed processing samples collected during the 2015 and 2016 ArcticNet cruises.
- Tremblay's team completed analysing nutrient samples collected during the 2016 ArcticNet cruises. $^{15}N/^{13}C$ data from incubations are being processed.
- The team now has access to two flow cytometers, which will enable to select populations of micro-algal cells for further taxonomic analysis.
- Postdoctoral fellow C. Dufresne is working on an upstream modeling project funded by the W. Garfield Weston Foundation. The goal is to use the Arctic CREG12 circulation model as forcing for the emerging phytoplankton communities model DARWIN (MIT) and study the dynamics of phytoplankton and zooplankton species assemblages. Dr Dufresne has already compared CREG12 model results in the southern Beaufort Sea/Amundsen Gulf and historical ArcticNet mooring data from this area. She is currently coupling the validated physical model results to the biogeochemical model.

RESULTS (Selected examples)

Since Arc3Bio is the continuity of projects initiated in previous phases of ArcticNet (and for which analyses are ongoing), the results presented here combine recent data with older ones obtained in the context of our oceanic time series.

1. Recent data on nitrate dynamics during the spring bloom in Southern Baffin Bay (Tremblay; HQP: G. Filteau). Contribution to NitrArc and GreenEdge.

Decreases in the seasonal persistence and thickness of sea ice and its associated snow cover are likely to result in early and enhanced penetration of sunlight to the water column during spring. This change is expected to advance the date of the spring phytoplankton bloom, possibly initiating it while the ice cover is still present and affecting trophic coupling in the food web. The magnitude of the bloom (i.e. total amount of biomass produced) is ultimately constrained by the availability of nitrate (the limiting nutrient for biological productivity in the Canadian Arctic), which is susceptible to be altered indirectly by ice loss (e.g. greater vertical mixing). Here we investigated the availability of nitrate as well as the timing and magnitude of its biological consumption during the spring bloom in southern Baffin Bay as part of the joint Arc3Bio/GreenEdge expedition (9 June - 10 July 2016). The parameter N* (calculated as the concentration of nitrate minus the concentration of phosphate times 16) provides an index of systemic nitrate deficiency and corresponds to the amount of nitrate that would need to be added to the system to allow microalgae to use all the available phosphate. Near-zero N* values in the waters flowing North in the Greenland sector of the Bay indicate that these waters have a balanced nutrient formula (no chronic nitrate deficiency), whereas the Arctic waters flowing South in the Canadian sector are clearly nitrate deficient (Figure 1). Observed surface concentrations of nitrate at the time of sampling were negligible in the Greenland sector but remained elevated west of the ice edge. The fraction of pre-bloom nitrate that had been consumed was very high near

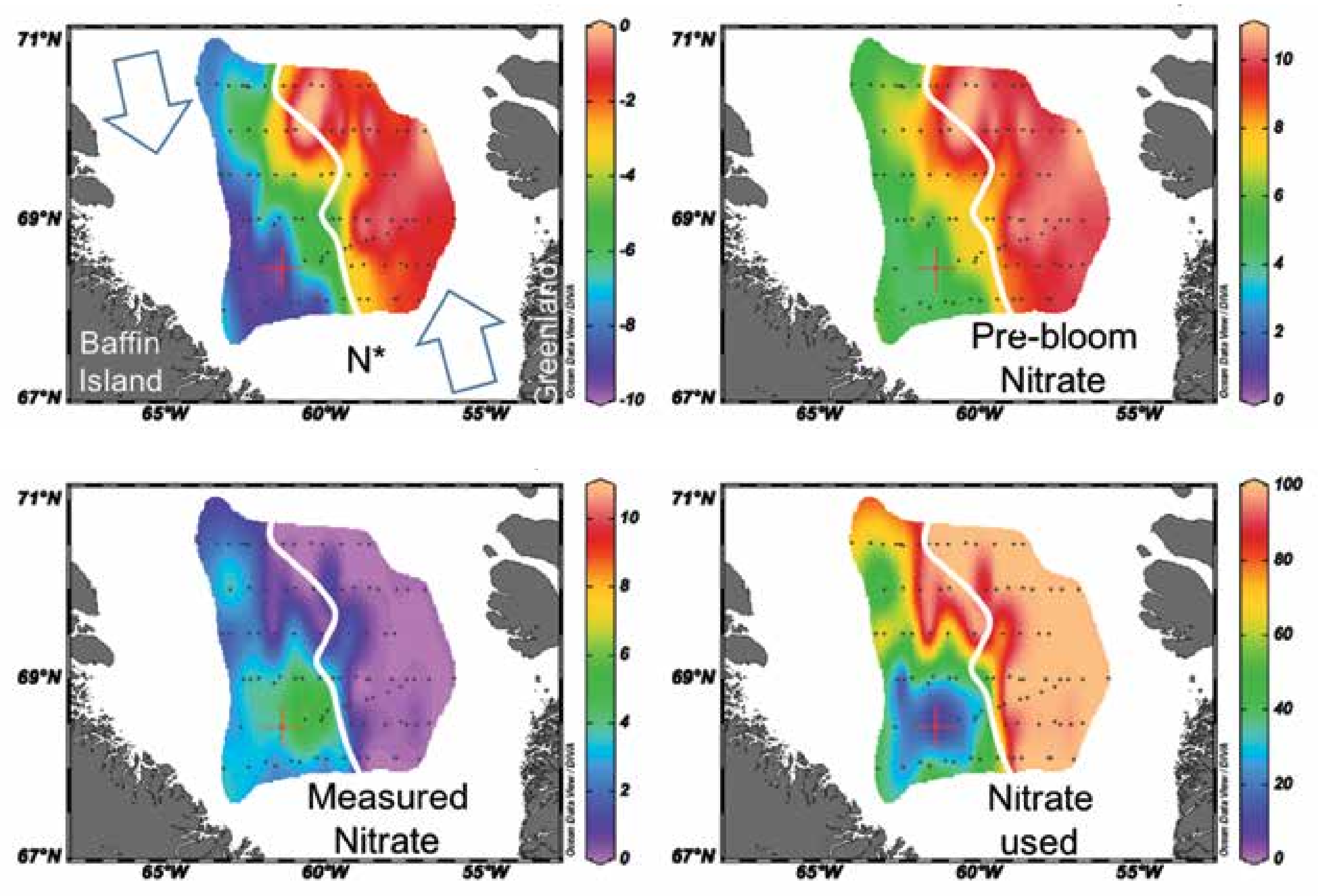

Figure 1. Distribution of the parameter N, nitrate concentration prior to seasonal bloom development (estimated), nitrate concentration at the time of sampling (observed), and estimated percentage of nitrate depletion during Leg 1 of the 2017 expedition of CCGS Amundsen (stations visited between 9 June and 10 July). The thick white line marks the approximate position of the ice edge on July 1st (ice-free waters are on the right) and block arrows indicate the prevalent direction of water flow.*

Greenland, but moderate to negligible west of the ice edge and within the Arctic outflow.

2. Ecosystem productivity in the marine waters of the Baffin Bay/Labrador Sea complex: climatology and trends based on remote sensing. (Bélanger, Tremblay). Contribution to ArcTrends and NitrArc (AACA report, in press).

Satellite-based estimates of primary production ranged from 5 to 100 g C m^{-2} y^{-1} on average for the period 1998-2014 (Figure 2), based on recent reprocessing with improved algorithms. Very low productivity levels analogous to those of a "desert" (purple shades) characterize most of Baffin Bay. Higher values are often observed along the Greenland coast, but the Baffin Island shelf exhibits extremely low coastal productivity across its entire latitudinal swath. Against this backdrop some areas stand out as being more productive, including the northern tip of Baffin Bay (North Water), Lancaster Sound, eastern Hudson Strait, Disko Bay, shallow banks of the west Greenland Shelf such as Store Hellefiskebanke and Fyllas Banke, as well as fjords with strong tidal mixing and marine terminating glaciers. These hotspots and many others have been formally identified as "Ecologically and Biologically Significant Areas" in Canada and a similar designation process is underway in Greenland.

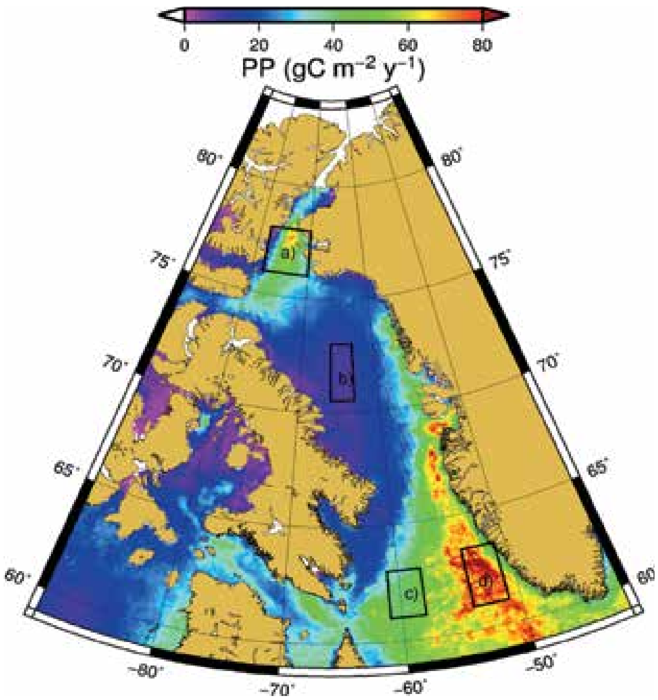

Figure 2. Satellite-based estimates of annual primary production averaged for the period 1998-2014 in Baffin Bay. Black boxes and letters indicate the areas selected for the analysis of temporal trends.

Overall, the Labrador Sea is more productive than Baffin Bay, presumably due to the deep convection and mixing that occurs there. Trend analyses (not shown here) show a modest increase of PP in central Baffin Bay (box b), no clear signal on the Greenland Shelf (box d), a decrease in northern Baffin Bay (box a, North Water) with indications of a recovery in recent years, and a persistent decline in the Central Labrador Sea (box c) (Tremblay et al. 2017, AACA report - in press).

3. Development of algorithms to improve the remote sensing of Arctic phytoplankton in the Baffin Bay region. (Bélanger; HQP: C. Goyens). Contribution to ArcTrends.

Satellite-based remote sensing of Arctic phytoplankton biomass and productivity is necessary to address change at synoptic scales but, as evidenced in the previous sections, remains challenging in polar regions and particularly along ice edges where most of the primary productivity is thought to occur. Potential contaminations imparted by highly reflective sea-ice edges in ocean color data are not detected nor corrected in the standard data processing chain. This contamination likely results in the inaccurate estimation of chlorophyll-a concentration. To address this issue, we investigated the detailed 3-D light field structure of the ice (anisotropy) and snow, as well as the optical properties of the waters adjacent to the ice edge, with the aim of developing new algorithms to detect and correct for contamination. We developed a new method to determine sea ice and snow reflectance anisotropy at an intermediate spatial scale (ranging from 1 to 80 m^2) using a fish-eye multispectral radiance camera (CamLum), which allows for instantaneous radiance measurements of a hemisphere at a high angular resolution. In addition, a hyperspectral field spectroradiometer was used to measure reflectance anisotropy at discrete angles in the 400-900 nm spectral range with a spatial resolution of the order of 10 cm. We also evaluated the performance of different atmospheric correction algorithms through an in situ versus satellite match-up exercise and investigated the possibility of improving these algorithms in the presence of sea-ice floes (Goyens et al. 2016). Figure 3 presents the retrieval of water reflectance in the blue portion of the visible spectrum (488 nm) using different atmospheric correction algorithms and show that the standard NASA algorithm (L2GEN) produces large uncertainties near sea ice (images on the left). An alternative method, named POLYMER (Poly) clearly improved the results.

4. Seasonal distribution of phytoplankton in relation to environmental variables in Labrador fjords, with special emphasis on Phaeocystis pouchetii. (Gosselin, Poulin; HPQ: A.G. Simo-Matchim; Coll: M. Ardyna, S. Lessard). Contribution to DiveArc.

We combined data from four years of investigation of the taxonomic composition of phytoplankton and other protists (>2 μm) in four Labrador fjords (Nachvak, Saglek, Okak and Anaktalak). Non-metric multidimensional scaling revealed that protist taxonomic composition was significantly different

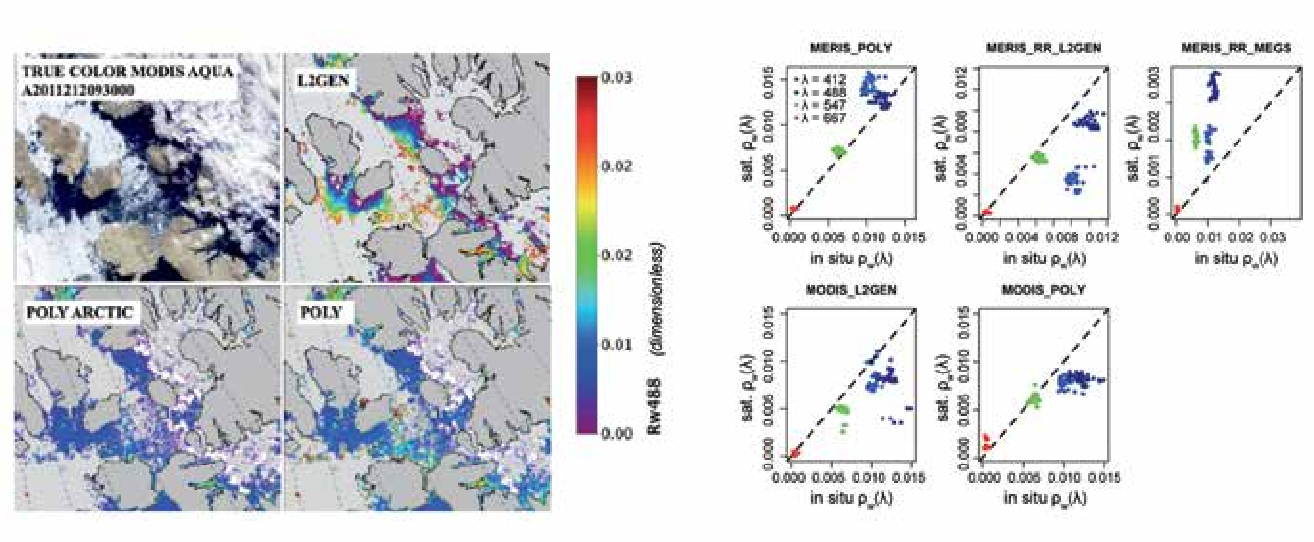

Figure 3. Left: True color MODIS Aqua image over the Canadian Archipelago in August and retrieved water reflectance at 488 nm images as processed using NASA standard L2GEN, POLYMER and POLYMER tuned for the Arctic waters, respectively. Right: In situ data collected during the ArcticNet cruise versus satellite water reflectance for three different atmospheric correction methods (POLY=POLYMER, L2GEN and MEGS) and for two sensors, MERIS RR (39 match-ups) and MODIS Aqua (44 match-ups) at 412, 488, 547 and 667 nm.

from one season to another (Figure 4). Significant spatial differences in protist composition were found only during summer 2013. During summer 2007, the community was characterized by centric diatoms and a mixed assemblage of flagellates (Figure 5a). In summer 2013, flagellates largely dominated the community and an intense P*haeocystis pouchetii* bloom was observed in Nachvak Fjord (18 x 10^6 cells l^{-1}) (Figure 5b). In early and late fall, the community was dominated by unidentified flagellates, prymnesiophytes, dinoflagellates and diatoms, in various proportions (Figure 5c, d).

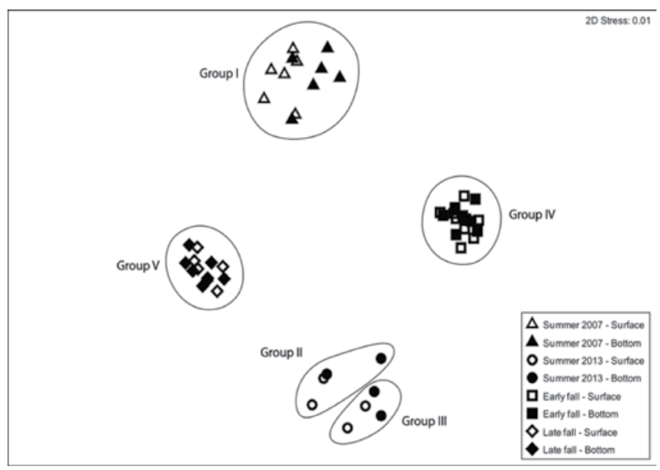

Figure 4. Non-metric multidimensional scaling (MDS) of the 49 samples collected in Nachvak, Saglek, Okak and Anaktalak fjords during summer 2007 (triangles), summer 2013 (circles), early fall 2010 (squares) and late fall 2009 (diamonds). Open symbols and closed symbols represent samples taken at the surface and bottom layers of the euphotic zone, respectively. Five groups of samples with similar taxonomic composition, as determined by the group-average clustering (at a similarity level of 40%), are superimposed on the MDS. From Simo-Matchim et al. (2017). © 2017 Inter-Research. © Simo-Matchim, Gosselin, Poulin, Ardyna, Lessard.

5. Structure and resilience of the benthic food web across the Canadian Arctic and the Chukchi Sea. (Archambault, Nozais; HQP: N. Friscourt). Contribution to DiveArc.

The changes now affecting the Arctic Ocean could alter the flow of carbon in food webs through a switch from the "ice algae-benthos" pathway to a dominant "phytoplankton-zooplankton" pathway as well as alterations in the functional type of phytoplankton dominating primary production. This may in turn alter the amount and quality of organic material that sediments to the seafloor and ultimately affecting benthic food webs that feed on it (Morata et al. 2008; Wassmann et al. 2011). We undertook a large-scale analysis of the structure and resilience (i.e., trophic separation and redundancy) of benthic food webs using the sea-ice biomarker IP25 and stable isotopes of carbon and nitrogen, with the aim of characterizing benthic food web structure in the Canadian Arctic and the Chukchi Sea. Results showed that benthic communities in the Beaufort Sea are depleted in ^{13}C, suggesting that they are fueled mostly by organic matter of terrestrial origin. By contrast, benthic communities of the North Water polynya relied mostly on ice algae highly enriched in ^{13}C (Figure 6). Indices of community structure vary among regions. For instance, trophic separation is highest in the Beaufort Sea, lower and similar in the North Water polynya and the Canadian Archipelago, and lowest in Amundsen Gulf. Redundancy is greatest in the Canadian Archipelago, intermediate in the North Water polynya and the Beaufort Sea, and lowest in Amundsen Gulf. Highest concentrations of IP25 in superficial sediments and zoobenthos are found in the North Water polynya and the Canadian Archipelago (not shown), indicating a transfer of sympagic material across several trophic levels through direct ingestion of ice algae or feeding on their primary consumers.

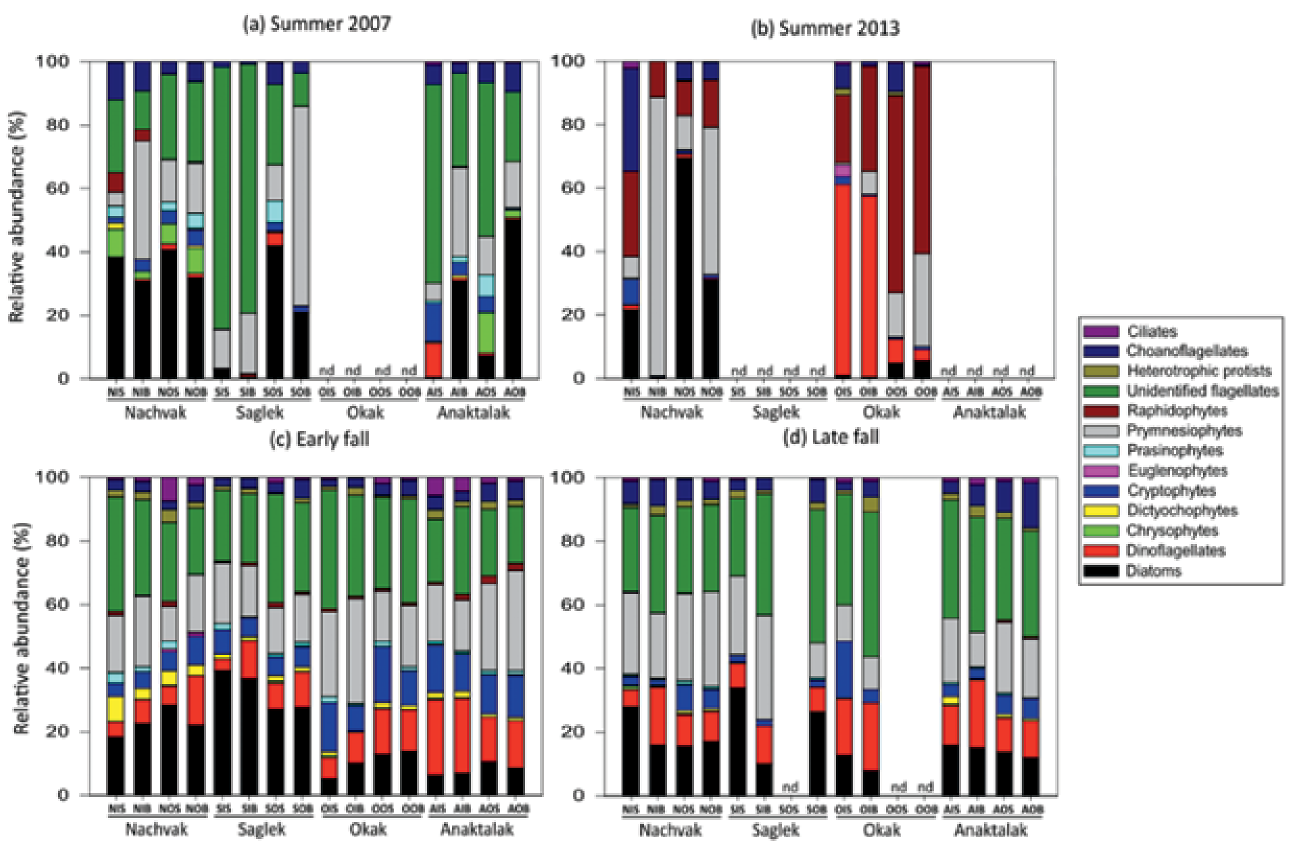

Figure 5. Variations in the relative abundance of protist groups at the surface and bottom layers of the euphotic zone in Nachvak, Saglek, Okak and Anaktalak fjords during (a) summer 2007, (b) summer 2013, (c) early fall 2010 and (d) late fall 2009. Codes indicate the fjord name (N: Nachvak; S: Saglek; O: Okak; A: Anaktalak), station location (I: inner; O: outer) and sample depth (S: surface; B: bottom). nd means no data available. Modified from Simo-Matchim et al. (2017). © 2017 Inter-Research. © Simo-Matchim, Gosselin, Poulin, Ardyna, Lessard.

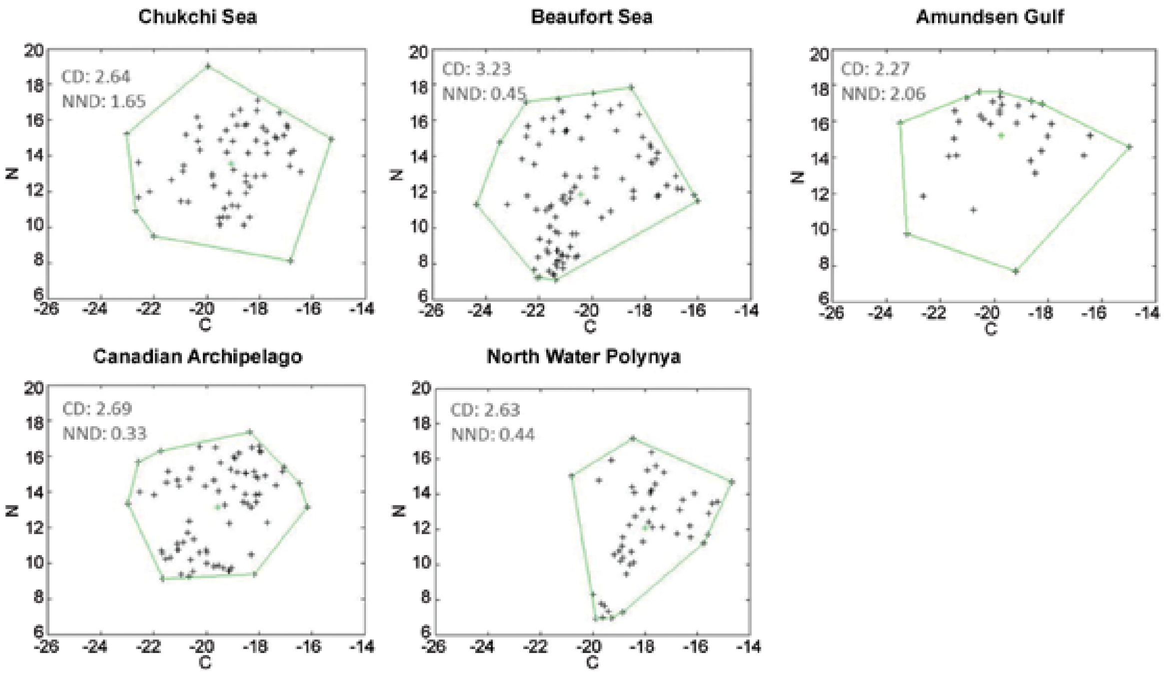

Figure 6. Mean isotopic composition of $\delta^{15}N$ and $\delta^{13}C$ of surface sediments from five Arctic regions (i.e. Chukchi Sea, Beaufort Sea, Amundsen Gulf, Canadian Archipelago and North Water).

6. Deep-sea ecosystem functioning in a changing climate: consequences of changing sea-ice cover for Arctic benthic ecosystems. (Archambault, Nozais; HQP: S. Bourgeois, G. Bravo, A. Mäkelä, Coll : U. Witte). Contribution to DiveArc.

It is unclear whether a switch from ice algae to phytoplankton as the first food source to the benthos in spring will negatively impact benthic consumers. Ice algae are regarded as a preferred food source for these organisms (McMahon et al. 2006; Hobson et al. 2002; Sun et al. 2009), but whether they would equally be able to meet their dietary and energetic requirements with phytoplankton detritus is unknown. The response of benthic communities to this shift will also affect the status of sediments as a carbon sink or source to the water column (Peck et al. 2010). In this work we investigated how a dietary shift from one food source to another may impact the algal-derived C and N uptake by macrobenthos, and consequently the rates of biogeochemical processing of algal C by comparing sites with contrasted inputs of ice algae and phytoplankton to the seafloor. We found that macrofauna was able to efficiently utilise both algal sources and that their delivery to the seafloor significantly enhanced benthic respiration and bacterial activity. In addition, we found no significant differences in the relative utilisation of both algal sources between major benthic taxa and between feeding guilds (not shown).

7. Seasonal patterns in Arctic prasinophytes and inferred ecology of *Bathycoccus* unveiled in an Arctic winter metagenome. (Lovejoy; HQP: N. Joli, A. Monier, R. Logares). Contribution to ArcTrends.

The pelagic ecosystem below the ice must survive during the winter and several questions remain regarding the types of phytoplankton that persist at different times and the strategies they used to obtain energy (mixotrophy, autotrophy?). The results presented here are from a new paper accepted in the

ISME Journal. It provides key information on the seasonal succession and potential loss processes of picophytoplankton under the challenging growth conditions of the Arctic during winter. Prasinophytes occur in all oceans but rarely dominate phytoplankton populations. In contrast, a single ecotype of the prasinophyte *Micromonas* is frequently the most abundant photosynthetic taxon reported in the Arctic from summer through autumn. In order to investigate the seasonal dynamics of prasinophytes outside this period, we analyzed high throughput V4 18S rRNA amplicon data collected from November to July in the Amundsen Gulf Region, Beaufort Sea, Arctic. Surprisingly during polar sunset in November and December, we found a high proportion of reads from both DNA and RNA belonging to another prasinophyte, *Bathycoccus* (Figure 7). We then analysed a metagenome from a December sample and the resulting *Bathycoccus* metagenome assembled genome (MAG) covered ca. 90% of the *Bathycoccus* Ban7 reference genome. In contrast, only ca. 20% of a reference *Micromonas* genome was found in the metagenome. Our phylogenetic analysis of marker genes placed the Arctic *Bathycoccus* in the B1 coastal clade (Figure 8). In addition, substitution rates of 129 coding DNA sequences were ca. 1.6% divergent between the Arctic MAG and coastal Chilean upwelling MAGs and 17.3% between it and a SE Atlantic open ocean MAG in the B2 Clade. The metagenomic analysis also revealed a winter viral community highly skewed toward viruses targeting *Micromonas*, with a much lower diversity of viruses targeting *Bathycoccus*.

DISCUSSION

1. The results indicate that ice dynamics and its influence on the penetration of sunlight in the water column is not necessarily the only nor the dominant factor affecting the timing and intensity of algal blooms in Baffin Bay (Figure 1). The nitrate deficiency observed in the Arctic waters flowing South in the Canadian Sector is large and can be linked to biogeochemical imbalances (i.e. denitrification) of the nitrogen cycle occurring in remote source regions of the North Pacific, the Bering Sea and the Chukchi Sea (Tremblay et al. 2015). This results in pre-bloom concentrations of nitrate (i.e. potential productivity) being half those estimated for the Greenland sector. In this setting the productivity of Canadian waters will be lower and occur over a shorter time span than in the Greenland waters arriving from the North Atlantic. Results also show that reduced ice conditions led to a large consumption of nutrients in the east, with 100% of the large pre-bloom inventory of nitrate gone. Seasonal consumption was delayed due to the presence of ice in the west, but data from the northwest corner of the survey grid suggest that 40 to 60% of the relatively low pre-bloom inventory

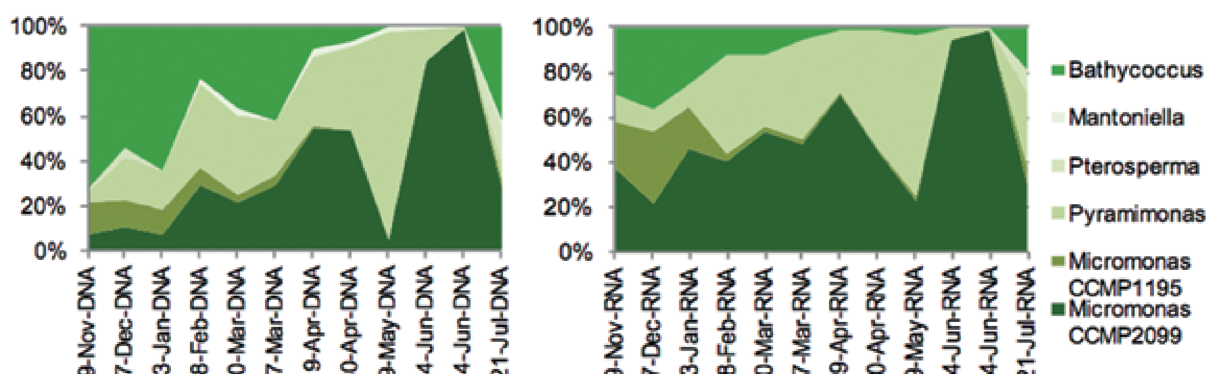

Figure 7. Proportion of prasinophyte taxa out of total prasinophyte reads (see above as Chlorophyta) from DNA (left) and RNA (right) templates.

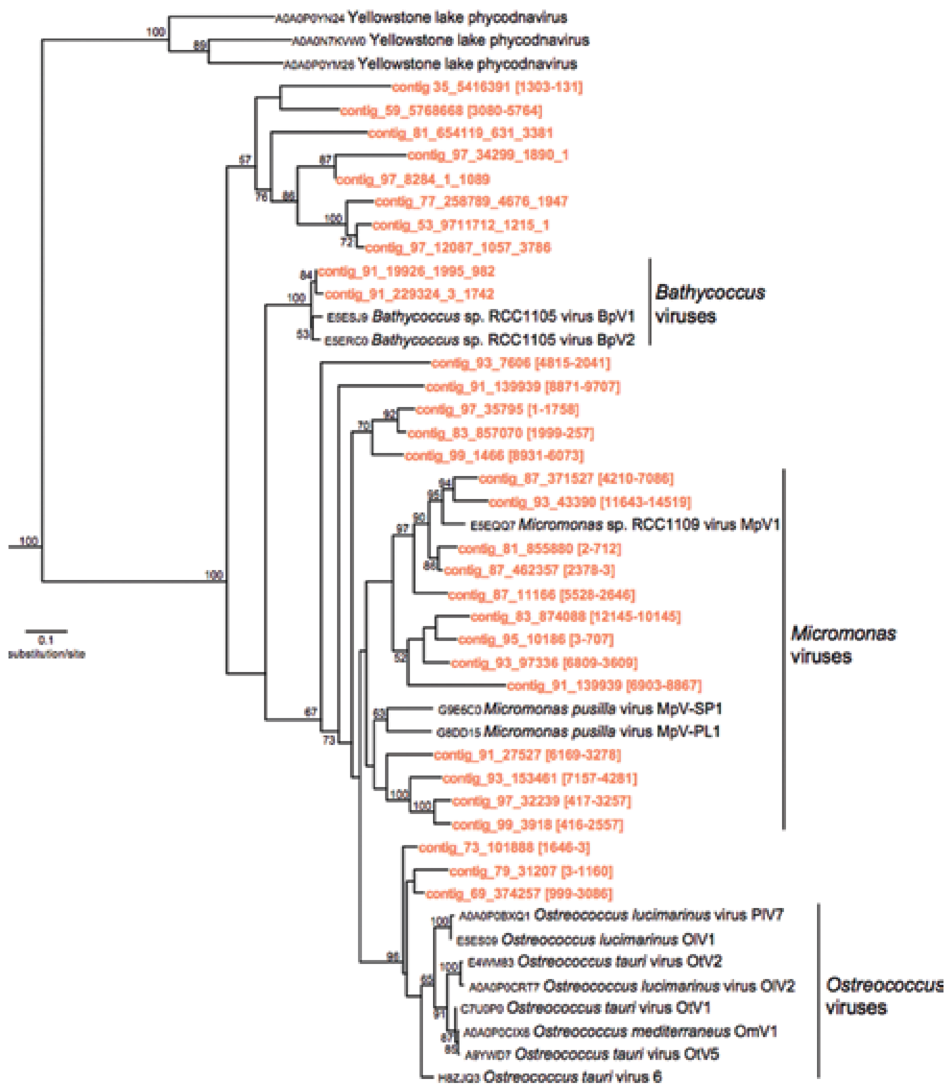

Figure 8. Phylogenetic tree of DNA polymerase B (polB) gene. ML reconstruction using model GTR+G based on a multiple sequence alignment of nucleotides. (Bootstrap replicate=100). Only nodes with bootstrap values > 50% are displayed. Contigs from the Arctic Bathycoccus MAG are in the lighter bold font.

of nitrate there has already been used beneath the ice cover. Corresponding values are much lower in the southwest, with only ca. 20% of the nitrate already consumed. This analysis suggests that a variable and possibly large fraction of the annual productivity in the Canadian sector.

2. The 1998-2014 climatology of satellite-based annual primary production in Baffin Bay is consistent with the prevalent southward flow of strongly stratified, partially nitrate-deficient surface waters in the west (see Figure 2). Yet, the east-west difference in productivity at a latitude of ca. 69°N (corresponding to the GreenEdge sampling area in Figure 1) is 6-7 fold, while our estimates of productivity based on the pre-bloom availability of nitrate is < 2.5 fold. This difference suggests that a substantial fraction of the primary

production occurring in western Baffin Bay is missed by satellites, presumably because a sizable fraction of primary production occurs beneath the sea ice (not visible) and the optical signal is contaminated near the ice edge as it retreats west. This analysis suggests that the "biological desert" (purple shades) depicted by Satellite data in the west is more productive than it seems.

3. The previous discussion underscores the need to re-assess and improve remote-sensing algorithms near ice edges (in Baffin and the Arctic in general). Goyens et al. (2016) confirmed the large errors imparted to remote-sensing estimates of productivity by the optical contamination of sea ice in the vicinity of ice edges. Our new results demonstrate the capability of the CamLum to measure reflectance anisotropy. Combining this approach with the ASD method allowed to exploit the best characteristics of both (namely high angular and high spectral resolution), producing a new dataset of snow and ice reflectance anisotropy that will help with the deconvolution of complex optical signals near the ice edge.

4. Sections 1-3 of the discussion have dealt with the magnitude and timing of productivity, but resolving the functional types of algae that dominate primary production is crucial to understand food web function. By combining our observations with those from the literature, we were able to suggest the following annual succession in the phytoplankton community of Labrador fjords: (winter) dinoflagellates and small flagellated cells -> (spring) diatoms from various genuses -> (summer) diatoms of the *Chaetoceros* genus, *Phaeocystis pouchetii* and *Chrysochromulina* spp. -> (fall) dinoflagellates, *Chrysochromulina* spp. and other flagellates. The main environmental factors affecting this succession differed from summer to late fall; a summer situation characterized by a strong stratification, higher incident irradiance and depleted nutrients in surface waters led into an autumn situation characterized by decreasing air temperature and irradiance. These conditions allowed cooling and a stronger vertical mixing of the water column. The general dominance of diatoms during summer (mainly *Chaetoceros tenuissimus* and the cosmopolitan *Chaetoceros gelidus*) should favor a productive herbivorous food and the export of carbon toward the seafloor and the benthos. The intense bloom of *Phaeocystis pouchetii* (18×10^6 cells l^{-1}) observed at the base of the euphotic zone in Nachvak Fjord in summer 2013 possibly implies an episodic collapse of the food web when conditions favors the production of this colonial algae. The dominance of fall communities by small flagellates (≤5 µm), prymnesiophytes (mainly *Chrysochromulina* spp. ≤5 µm) and dinoflagellates (mainly *Gymnodinium/Gyrodinium* spp.) suggest a recycling system with a low potential for carbon transfer toward the upper echelons of the food web.

5. By using a stable isotope approach, regional differences in the resilience (i.e., capacity for recovery and ability to adapt to new conditions) of the benthic trophic structure in the Canadian Arctic (Figure 5) were found. We anticipate that benthic trophic structure in the Amundsen Gulf will be more sensitive to natural or anthropogenic disturbances than in the Canadian Archipelago and the North Water polynya. We have also provided new IP25 data to assess the transfer of ice algae to the benthic food webs across the Canadian Arctic. We have shown that ice algae could be the primary source of carbon for these food webs, even during fall. The firm link between ice algae and zoobenthos was particularly noticeable in two of the studied regions; in the Canadian Archipelago and in the North Water polynya where we measured IP25 highest concentrations in surface sediments and zoobenthos. These results contribute to increase the baseline data on the structure of benthic food webs in the Canadian Arctic.

6. Overall the Arctic macroinfauna shows dietary flexibility and appears to utilize a variety of food sources, safeguarding them from the predicted climate-driven alterations to the benthic food

supply. These findings generalize our previous observations (Gaillard et al. 2015), suggesting Arctic benthic fauna engage in highly opportunistic feeding. As the responses of fauna to ice algae and phytoplankton were site-specific, it is likely that local local environmental conditions play a significant role in determining the responses of fauna to different food sources. A pulse of phytodetritus to the seafloor triggered an immediate response by the benthic macroinfauna and bacteria regardless of the type of algae added. The benthos efficiently utilized both ice algae and phytoplankton as a food source, and the overall algal C and N uptake rates appear higher in the Arctic sediment than in temperate deep sea sites. Respiration was identified as a major pathway for the processing of algal-derived C. Due to the observed flexibility in food utilization, Arctic benthic communities could benefit from the predicted increases in rates of primary production and consequent food supply to the seafloor.

7. Overall, a combination of *Micromonas* being relatively less able to maintain activity under dark winter conditions and viral suppression of *Micromonas* may have contributed to the success of *Bathycoccus* in the Amundsen Gulf during winter. The percentage of the *Bathycoccus* genome length covered by MAG contigs recovered from our winter whole-community metagenome indicates a high abundance of this species in the December sample. The unexpected dominance of *Bathycoccus* in winter Arctic waters contrasts with the lower abundance of the normally dominant Arctic *Micromonas* ecotype. The metagenomic data indicated that the winter *Bathycoccus* fell within the coastal B1 clade. The high diversity of prasinovirus polB virus in the winter metagenome was consistent with a viral control on *Micromonas*, combined with *Micromonas* being relatively less able to maintain activity under dark winter conditions.

CONCLUSION

This year's report presented recent novel data and advanced the interpretation of time series data we have been collecting for many years. We showed how chronic nutrient deficiency in the western side of Baffin Bay keeps its productivity low with respect to other sectors. The observation of nitrate consumption under sea ice suggests that a non-negligible fraction of annual productivity in eastern Baffin Bay is not captured by remote sensing, which is also subject to error near ice edges. We are pursuing a promising means to address the latter issue. The dietary flexibility of benthic consumers suggest that their communities are resilient to the expected shift from ice algae to phytoplankton as the ice continues to dwindle, and should therefore benefit from the predicted increases in primary production and ensuing food supply to the seafloor. Regional differences in the resilience of benthic assemblages indicates that the western Canadian Arctic may prove more sensitive to natural or anthropogenic disturbances than the Canadian Archipelago and the North Water polynya. We also advanced surveys of planktonic protists, developing a better understanding of their responses to the physical environment and addressing issues that complexify biodiversity assessments (e.g. seasonality, life stages).

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SECTION II. TERRESTRIAL SYSTEMS

Section II is composed of 10 ArcticNet research projects covering several biological, ecological, biogeochemical, meteorological and physical components of the Canadian Arctic terrestrial systems.

PERMAFROST RESEARCH FOR NORTHERN INFRASTRUCTURES AND IMPROVED COMMUNITY LIFE

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Modélisation de l’avancée des espèces arbustives dans la région d’Umiujaq, Nunavik - Spatially explicit modelling of increasing shrub cover in the region of Umiujaq, Nunavik

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ABSTRACT

This project is partly a continuation of ArcticNet's Project 4.4 Permafrost and Climate Change in Northern Coastal Canada. For the next three years, the focus of the research and knowledge transfer efforts will be directed towards the support of infrastructure maintenance and construction for the development of the Arctic and to the wellbeing of communities who live on the land, while still making high-level scientific contributions to permafrost science and engineering. Building on previous research results and contributions to ArcticNet's objectives in situations where permafrost is a key factor, this project has five overarching and interrelated objectives: 1- To map and improve knowledge of permafrost characteristics and temperature regime in a number of Inuit communities and in support of a number of infrastructure improvement or construction projects such as airports, roads and sea ports. 2- To provide informative support and advice necessary to select best choices of foundations for all types of buildings in communities, improve land use planning, better design urban architecture and better manage lands in general. 3- To create a teaching tool and a computer-assisted course on permafrost for widespread Inuit and public use. 4- To develop and test new engineering designs and materials for roads, airports and coastal infrastructures. This objective includes the design of a risk management process to help selecting the best strategies for the construction and the maintenance of roads, airports and coastal infrastructures. 5- To provide opportunities for the members of the research team and their students to carry innovative research in permafrost science and engineering as the project will take them to a number of different geological, climatological and geomorphological contexts across the Arctic. Indeed, new approaches for the characterization of permafrost properties will be developed, making use of emerging technologies such as measurement of ground displacements by satellite-borne Interferometric Synthetic Aperture Radar, permafrost characterization by CT-Scan, new methodologies for measuring in situ terrain changes (laser scanning) and measuring unfrozen water contents, and improved approaches in interpreting geophysical surveys such as Electrical Resistivity Tomography and Ground Penetrating Radar. Another fundamental component of the research relates to vegetation and ecological changes associated with climate change and permafrost decay in order to assess how the land that supports resources for the Inuit is being affected, for example through loss of berry producing terrains, changes in habitats for herbivorous species (e.g. caribou feeding grounds) and changes in terrain accessibility through topography changes and increase soil sensitivity to disturbances. The team members will work in close collaboration with other ArcticNet projects, particularly those dealing with capacity building in coastal communities and with housing and health issues. The project is already supported by research agreements, collaborations and contracts from provincial, territorial and federal ministries and some new external funding and in-kind contributions are expected over the project's course, given the urgency of the matter. A large part of the requested funding will provide support for keeping key professional staff, stipends for a number of graduate students, field expenses, participation to the ArcticNet's Annual Scientific Meeting and networking, thus providing adding value to the whole.

KEY MESSAGES

- A new permafrost, ground ice contents and ground temperature map of Nunavik is now available. The large scale of mapping (1 km^2) makes it a powerful information tool to support environmental stewardship and economic development.
- The coastal survey and classification of Nunavik is now 80% complete after two years of this project.
- The team run large scale permafrost studies in support of economic development in the Kivalik region of Nunavut.

- Field studies that were continued in the Lac De Gras area of NWT revealed that the concentration of soluble cations in the active layer and near-surface permafrost of mineral soils is about one order of magnitude lower than reported in previous studies from northwestern Canada. This suggest that similar shield areas may be poorly represented in global assessments of permafrost geochemistry.
- This study in the Lac De Gras region shows that near-surface mean annual ground temperature (2015/2016) in a gently rolling tundra area on the Canadian Shield varies by more than 7 °C within only few kilometers. Fine-scale differences of up to 2.5 °C in mean annual near-surface ground temperature were observed within less than 10 metres. Choosing only one or few such locations for global model testing can lead to results which do not represent true landscape characteristics well.
- After climate warming of 3 °C over the past 27 years in Narsajuaq near Salluit, the significant increase of active layer thickness in organic-rich soils was nevertheless insufficient to provoke the thawing of deep ice wedge tops. Only the outgrowth forms from the previous cooling period have thawed so far.
- Wet moss cover and peat have likely expanded with climate warming, along with shrubs at Narsajuaq, therefore increasing somewhat the insulation properties of the soil surface. Doing a final heat balance of the changing conditions is planned.
- Shrubs tend to colonize more readily low-elevation areas and moderate slopes, while their cover is more likely to increase around existing shrub patches.
- The predicted probabilities of shrub increase in the region of Umiujaq were consistent with patterns of change inferred from field data, but not from recent increases in NDVI.
- Hazard mapping was in demand from communities and regional governments. One map was made for the village of Old Crow in Yukon and six were done for villages in Nunavik.
- Sustainable development of Arctic communities involves the expanding, researching and proving the methods to prolong the life of northern infrastructure.
- New instrumentation was installed under the Iqaluit airport runway to monitor the performance of the designs of the repairs that are being done to fix the damage of thawing ice wedges under the infrastructure. Long term monitoring is needed.
- Our monitoring shows that the stability and safe operation of roads and runways built on permafrost are very sensitive to inter-annual climate variations that regulate maximum thaw depth penetration in embankments and in the foundation soils. Adaptation to climate changes starts with the current situation.
- The above observation justifies the need for development of a risk analysis approach to better plan and coordinate progressive adaptation measures to avoid loss of capacity and large economic costs in the future.
- The risk analysis needs to be quantitative and based on site-specific data.
- Consequence calculations from the risk assessment can be used within cost/benefit analyses to aid decision makers in determining what adaptation or mitigation methods are warranted.
- *PermaSim* training software was further developed: Modelization of soil temperatures was done from modelled air temperatures for three periods: 1995-2015, 2040-2060 and 2080-2099; parameters included five soil types (clay, silt, sand, rock, peatmoss), four plant covers (high shrubs, low shrubs, lichen, none), and a depth up to 5 m (0.5 m increments).
- Avativut Program: Two hands on workshops on Berry, Ice and Permafrost LES were organized successfully in Inukjuak and Umiujaq. As a result, it generated a great interest from Inuit participants for this program and prompted a

better collaboration between Math & Science teachers and Inuktitut & Inuit culture teachers.

- Interactive and graphic outreach material are being developed to engage students with the Avativut Program and the data they collected with their teachers.

INTRODUCTION

Soil or rock at temperatures permanently below 0 °C (the standard definition says for a minimum of two consecutive years), permafrost is a climatic phenomenon because its very existence depends on a cold climate with mean annual air temperatures below 0 °C. It is also a geological phenomenon; soil particles and organic matter in permafrost are bonded together by ice under a variety of forms and origins, therefore creating a large number of "geocryological" facies. Permafrost manifests itself in the morphology of landscapes by multiple landforms such as tundra polygons, frostboils, palsas, pingos, lithalsas, permafrost plateaus and many others. Under the context of climate change, permafrost is at the core of most issues important for ecological changes in the natural environment and for community and infrastructure development (i.e. construction, maintenance, land use planning) because the terrain is destabilized when it thaws. Thawing of permafrost generates landslides, thaw settlements and depressions, many of them filled by small ponds called thermokarst lakes. Vegetation height and density as well as snow cover depth and structure also regulate ground temperatures, sometimes helping maintain, often leading to thawing of permafrost. Since permafrost is the ground that supports terrestrial ecosystems, its thawing provokes major ecological changes. Topography is changed, slopes are destabilized, soil drainage is modified, previously frozen carbon and chemicals are released in the environment, soil horizons are disturbed, microclimates are modified, vegetation changes and new plant associations come in sequence, with ultimately impacts on the food chain, potentially up to human harvesters. This is actually occurring over vast areas across the northern regions. Indeed, permafrost is warming across the Arctic and its progressive disappearance is reported in the scientific literature and in the media, particularly at the southern fringe of its distribution area, called the discontinuous permafrost zone. Permafrost thawing under roads, airport runways, buildings and communities may provoke costly damages that affect the quality of life in many ways, from damaging houses to making infrastructure unusable. The impacts of failing infrastructure can be significant and include higher maintenance costs, performance reductions, and loss or decrease in capacity. Other less tangible impacts include decreasing quality of life and increasing health and safety risks. There is a need for better permafrost characterization to remediate failing infrastructure and to build new infrastructure. A risk assessment process is also required to aid in selecting the best strategies for the construction and the maintenance of infrastructure built on permafrost for the warming years to come.

This multidisciplinary project "Permafrost research for northern infrastructures and improved community life" brings together a team of five researchers networking with multiple collaborating individuals and organizations. The overall goal of the project is to contribute to the increase of the level of basic and practical knowledge on permafrost issues, to identify solutions, develop innovative research approaches and, most importantly, share knowledge and provide learning opportunities to regional governments, decision makers and members of northern communities. The core team is composed of five university professors-researchers who contribute to training the upcoming generation of permafrost scientists, engineers, professionals and Northeners. The regions where the research takes place span across northern Canada, from Yukon to Nunavut and Nunavik. The many individual projects of the team members are carried out with their students and their support staff and in partnership with local, regional and national organizations, thus constructing a maze of collaborators and knowledge sharing with ArcticNet at its core.

RATIONALE OF THE PROJECT AND GENERAL OBJECTIVES

We focus the research and knowledge transfer efforts on the support of infrastructure maintenance and construction for the development of the Arctic, addressing knowledge needs both for major transportation infrastructure such as airports and highways, for mining and for housing construction and land use planning in local communities. We collaborate with regional governments and encourage the development of public policies to improve the quality of housing and life in northern communities. We also address how the warming and thawing of permafrost has impacts on vegetation and animal resources through disturbances and ecosystem shifts, with a potential cascading effect on food resources and quality of human life.

By using our experience in field and laboratory research and by testing new measurement technologies for permafrost characterization we aim at making high-level contributions to permafrost science and engineering.

This project addresses permafrost related issues such as the analysis of permafrost conditions in the local and regional geological and ecological contexts, characterization of permafrost properties with proven methods and instrumentation, observing and measuring ecological changes, designing and testing innovative methods. The project also has a coastal geomorphology component in order to address some combined sea-ice and permafrost-related issues along shores, for instance in view of potential marine infrastructure improvements, be they small facilities in communities or major installations for industrial projects.

Finally, we wish to contribute to fulfill the need for an increased number of Inuit, both young and mature, to acquire a fundamental understanding of permafrost science, particularly on the basics of ground temperature regime, processes of thaw, and the forms of ground ice found under various landforms. A better understanding of how buildings and infrastructures interact with the permafrost thermal regime and ground stability is an urgent need to fulfill for northern residents in order to improve their capacity for decision-making in matters of construction, community planning and environmental impact analysis over their lands. Understanding the basic principles of permafrost science is necessary also to maintain better practices in municipal activities such as excavations, snow removal, ditch digging and road maintenance, for instance. Knowledge and a "culture of permafrost" would provide some empowerment of residents and make them highly competent in matters of land development in general.

Given the above, the three-year objectives of the project are:

1. Mapping of permafrost extent and properties, and measurements of the thermal regime at all scales, in communities, and along coastlines. General studies of permafrost and regional scale mapping supports science and policy making at the regional level, for instance at the scale of IRISes. Mapping at the scale of communities (1-2 km^2) supports the choice of foundation types for buildings of various sizes and functions and assists in urban planning. Periglacial coastal processes are studied also along shorelines to help classify coastal ecosystems and provide knowledge for the construction and improvement of maritime infrastructures.
2. Permafrost knowledge transfer and technical support to communities: To provide support, through presentations and discussion sessions in communities, information and advice necessary to select best choices of foundations for all types of buildings. To provide informed technical support to communities for them to improve their land use planning, design their urban architecture and manage their wider lands.

3. Development of a teaching tool for Inuit and other stakeholders: To create and trial a teaching tool and a computer-assisted course on permafrost for widespread Inuit and public use.
4. Support of infrastructure renovation and construction. To work in collaboration with ministries and private sector parties involved in infrastructure renovation and construction to design better adaptation strategies, particularly for roads, airports and ports and to develop and test new engineering designs and materials for roads, airports and coastal infrastructures (e.g. convection embankments, heat drains, pre-thawing of permafrost, active and passive heat exchange systems, etc.). This objective includes the design of a risk management tool to help select the best strategies for the construction and the maintenance of roads, airports and coastal infrastructures.
5. Development of innovative approaches and technologies: To keep developing new methods for measurement and model-based predictions of permafrost terrain dynamics and ecological changes. To innovate ways to measure permafrost properties such as unfrozen water content, ice content and structure, and thermal properties (conductivity, heat capacity). This objective involves the use of new technologies such as InSAR, laser scanning, improvements in ground penetrating radar (GPR) interpretation and electrical resistivity tomography (ERT) interpretation as well as improved drilling techniques. As the measurement of temperature alone is of limited value for describing thawing permafrost, the development and use of new technologies capable of measuring latent heat effects in the ground is a basis for future monitoring in the environment and for early warning with respect to infrastructure integrity.

KNOWLEDGE MOBILIZATION

Creating new knowledge, sharing and making it available for individual northerners, communities, governments and infrastructure owners and operators is an integral part of all the research work and the objectives of the project.

Team research approach

Being involved with a number of communities and infrastructure projects across the Canadian Arctic offers the team a great potential to sample permafrost under a variety of terrain and climate conditions, to study geomorphic processes, to install monitoring instrumentation and to test innovative technologies. Working with university, public and industrial partners over a geographically spread network of communities and infrastructure projects is therefore a very beneficial research strategy for the team. Our approach is therefore one of an "applied and socially involved" fundamental research.

ACTIVITIES & RESULTS

1. Mapping of permafrost extent and properties, and measurements of the thermal regime at all scales, in communities, and along coastlines.

Mapping permafrost temperature and geocryological properties in Nunavik

Under a research contract with Ministère des Forêts de la Faune et des Parcs (MFFP) du Québec, the mandate was given to produce a high resolution (1 km^2) permafrost map of Northern Québec. The rationale behind the mandate is to provide baseline information on terrain conditions for regional development, with applications to the planning of new transportation corridors, mines, airports and ports (see also coastal mapping below).

The mapping methodology requires the introduction of several physical inputs obtained from climate and geological data. The near surface air temperature data used for calculating ground surface temperatures over the territory is borrowed from Way et al. (2016) that have produced a surface temperature matrix at a resolution of 256 m^2 from various reconstruction models and data from Environment Canada. The dampening effect of the buffer layer (i.e. the vegetation cover and the snow cover) on heat exchanges between the atmosphere and the soil surface was computed with the standard approach of n-factors. Thawing n-factors in summer time were attributed to the land cover type map units produced by the Canada Center for Remote Sensing.

Finding or estimating freezing n-factors to apply over the map area was more difficult and less straightforward because a high resolution map of snow cover depth at the end of winter was needed in practice, something that no remote sensing technology or model can yield currently. However, the abundant literature illustrates and provides n-factor values in relation with vegetation cover types since snow depth and density is closely related to sedimentation conditions under different vegetation heights and density. Topography also plays a major role in snow depth variations in the landscape because of wind drifting, erosion on summits and flat lands and deposition on slopes in depressions. This factor becomes dominant beyond the tree line and the shrub tundra zone. A composite index allowing calculation of potential snow cover depth was created purposely for the mapping exercise. Fifty percent of the index value is given to the vegetation types of the CCRS map, and the other 50% is calculated according to a topographic index that maps and calculates areas of high and flat, wind exposed surfaces, vs slopes and valley bottoms favourable to snow accumulation. The numerical terrain topographic data used to determine the topographic index is the Canadian numeric elevation model at the resolution of 23.2 x 23.2 m. In our application, the relative elevation differences were smoothed at 100 m resolution. The snow cover depth values calculated over the total area for the 1 km^2 pixels were used to derive the freezing n-factors.

Application of the TTOP (Riseborough et al., 2008) model allowed for the calculation of each 1 km^2 pixel the temperature at the surface of permafrost, based on climate data averaged from 2006 to 2013.

Variable soil thermal conductivity values (frozen and unfrozen conditions) over the region were attributed

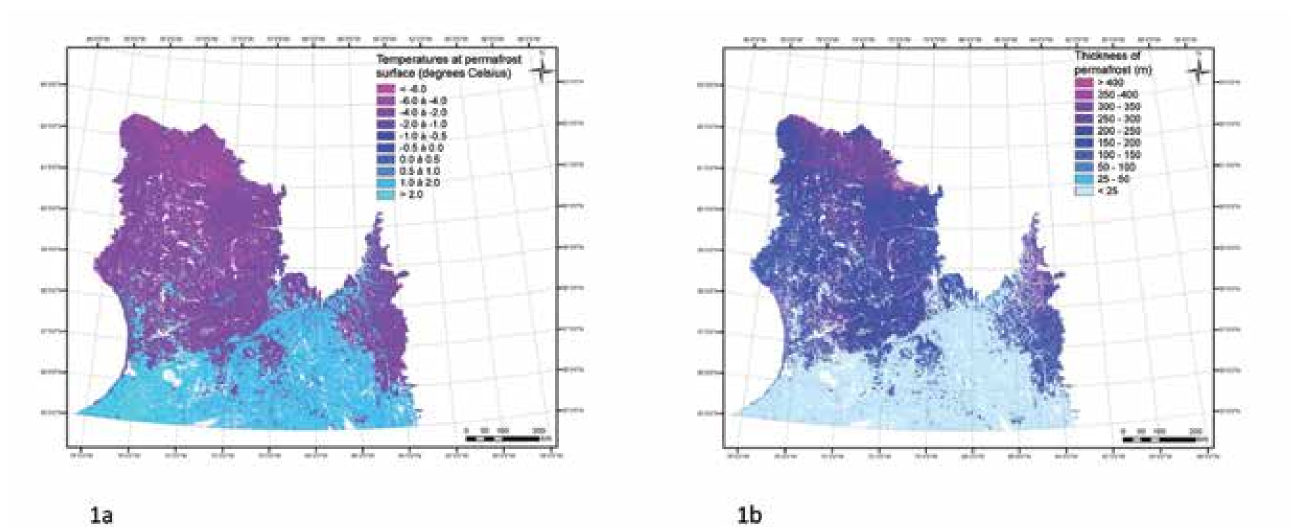


Figure 1. a) Map of permafrost surface temperatures (distribution where this value is ≤ 0 °C) and b) map of permafrost thickness.

to each class of surface geology materials that appear on the surficial geology map produced by the private sector for the government of Québec at a 1 km^2 resolution. Classes of permafrost ground ice contents were also determined according to ice content data obtained on all types of surficial material (rock, till, sand, gravel, silt, clay, peat) from our many drilling operations in Nunavik and data in the ADAPT base. Finally a basal thermal heat flux of 40.26 mW/m^2 obtained from the literature (Majorowicz and Minea, 2015) was applied to the permafrost general equation to calculate permafrost thickness (i.e. depth of the base of permafrost). A more complete description of the complete mapping methodology can be found in L'Hérault et al., (2017).

The new maps of permafrost surface temperatures (thus permafrost distribution where this value is ≤ 0 °C) and permafrost thickness are shown on Figure 1 a and b. They bring new information relative to the recent mapping by Way et al., (2016), by adding ice contents and an advanced representation of snow cover distribution and thickness. Improvements are expected in the next edition of the map when the 1 km^2 vegetation cover map of MFFP will be finished and transferred to us; the mapping and the precision of the n-factors will be greatly improved, thus yielding still better precision of permafrost temperatures across the region. These new permafrost maps will be included as key documents in the second iteration of ArcticNet's IRIS-4 second iteration.

Nunavik coastal mapping and classification

Surveying the coastline of Nunavik was continued for the second year in 2016 wit co-funding from ArcticNet, CEN and MFFP, and with the in-kind support of Environment Canada for the lending of videographic and photographic equipment and the use of its e-Space GIS software. The coastline of southern and western Ungava Bay and Hudson Strait was filmed and pictured. The stretch covered in 2015 extends from Kangiqsualujjuaq to Deception Bay. So far poorly known coastal periglacial features were found along

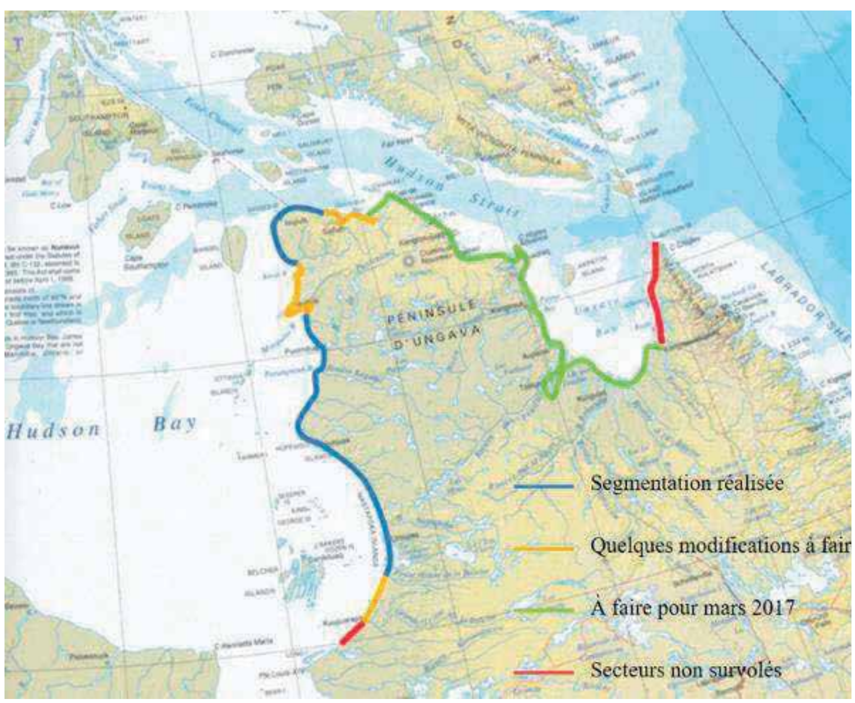


Figure 2. State of advancement of the Nunavik coastal classification.

Figure 3. Examples of landforms observed along the coastline of Nunavik.

this poorly documented shoreline such as succession of raised lagoons delineated by boulder barricades. All the large tidal flats in the megatidal environment of Ungava bay (18 m tidal range) were mapped. The survey extended to the large estuaries of the George, Whale, Koksoak, Leaf and Kangirsuk rivers. Special attention was paid to maritime infrastructure in communities and to ports of mining companies. The coastal classification and the construction of conceptual models of coastal evolution of peculiar shoreline segments is the subject matter of A. Boisson's Ph.D. thesis. Other students use the data to classify sections of the shoreline as undergraduate thesis work. The precise mapping and description of southern Ungava Bay tidal marsh will be the topic of L. Poulin-Leboeuf's M. Sc thesis. Figure 2 shows the state of advancement of the Nunavik coastal classification, to be included as a new chapter into IRIS-4 second iteration. Figure 3 (a to d) shows examples of the landforms observed along the coastline.

The geological information from this survey was transferred to WFNStrategies Inc. and to the KRG for the routing of the planned Fiber Optics communication cable from the sea floor to land in communities, a project by the KRG and the Québec Government for improving communications in Nunavik, Southern Baffin and Nunatsiavut.

Permafrost studies in the region of Rankin Inlet, Nunavut

The western coast of Hudson Bay in the Kivalliq region of Nunavut is undergoing significant infrastructure development associated with natural resources and community sustainability. Establishment of a road or hydropower corridor between Manitoba and the Kivalliq region has been under consideration for several years. Permafrost and ground ice are important features of this landscape that can significantly affect ground stability and land-based infrastructure. Knowledge of permafrost conditions is required to characterize climate change impacts, reduce risks and aid in adaptation solutions for the region. However, there is limited historical or contemporary permafrost data along the western coast of Hudson Bay. Although ground temperature data are collected as part of natural resource projects such as Meadowbank and Meliadine, these data are often site-specific and limited in recording period, or are not publically accessible beyond data released in environmental assessment reports. Without fundamental knowledge of past and current permafrost conditions, any response of permafrost or landscape change to climate warming is difficult to establish.

A collaborative activity between the Canada-Nunavut Geoscience Office, the Geological Survey of Canada and Yukon Research Center was initiated to provide geoscience information on permafrost and landscape conditions for infrastructure and community development along the western coast of Hudson Bay. Objectives of this activity include:

1. collection of valuable baseline terrain and permafrost information in the Kivalliq region of Nunavut (surficial geology, land cover, periglacial landforms, ground temperature),
2. development of methods for regional characterization of permafrost conditions by integrating observations from different sources across different scales from site-based to remote sensing systems, and
3. understanding permafrost conditions and the potential response to infrastructure development and climate warming for the Kivalliq region of Nunavut.

Fieldwork in 2016 involved geomorphological observations, examination of surficial geological materials, and site selection for permafrost monitoring stations. Initial sites at Rankin Inlet and Ennadai Lake were instrumented with ground temperature sensors. Additional site locations were chosen to represent a variety of conditions including developed and undeveloped land, and different geological settings.

The full suite of observations will include sediment sampling, permafrost coring and measurements of ground temperature, water content and ground movement.

Site-based observations will be used in next phases of the project for thermal modelling and analysis of geophysical and satellite data for mapping of ground movement and landscape classification.

Regional permafrost studies in the Lac de Gras region in NWT (and interregional comparisons in Yellowknife and Umiujaq)

We have obtained the first year of data from a network of 40 permafrost measurement sites established in the tundra near Lac de Gras, NWT in 2015. This was a collaboration with the Northwest Territories Geological Survey in the the Slave Province Surficial Materials and Permafrost Study funded by the Canadian Northern Economic Development Agency and industry partners.

Initial results show that near-surface mean annual ground temperature varies by more than 7 °C between plot averages. These are based on four independent data loggers within each 15 m x 15 m plot. Within plots, differences of up to 2.5 °C in mean annual near-surface ground temperature were observed. These findings are relevant as they underscore the need for careful spatial sampling when provisioning thermal data for the validation of regional and global permafrost models. The Lac de Gras thermal data has been cleaned and quality controlled and will be published in a data journal during 2017. Its detailed analysis is the focus of an ongoing Masters thesis.

For the thermal data collected at Lac de Gras and the growing Northwest Territories Permafrost Database, we have developed several prototype applications for data processing and data cleaning. The database structure developed allows query access to support large-scale model testing and is designed around having digital object identifiers for each measurement to support data publishing

Figure 4. Previously un-sampled rock surface temperature at Umiujaq.

and the retrieval of references together with large data sets. This is run by a research professional with the support of two undergraduate students and two Masters students.

The boreholes drilled in the Lac de Gras campaign provided many samples from soil pits and drill cores. Their analysis lead to new findings: the absolute concentration of soluble cations in the active layer and near-surface permafrost of mineral soils is about one order of magnitude lower in the Lac de Gras area than reported in previous studies from northwestern Canada. As organic soils are enriched with solutes relative to tills and glaciofluvial deposits, and since the organics are primarily at the surface or within the active layer, the active layer in the Lac de Gras region is solute rich with respect to underlying permafrost. These findings are based on more than two hundred permafrost and active layer soil samples taken during 2015. Given the environmental setting of ablation till mostly sourced from igneous rock, this results is not surprising. It does however help to put into context the application of previous research findings over all of Canada when assessing climate change impacts on soil, water chemistry, and ecosystems.

Following the approach used at Lac de Gras, we have instrumented sites around Yellowknife and near Umiujaq. The aim of this spreading of data collecting sites is to generate a database of ground thermal data suitable for evaluating permafrost models driven by climate simulation data. Specifically, we aim at having supersites in major climatic zones and for each of them to have spatially distributed measurements in the most relevant terrain types, i.e. being able to include large local permafrost thermal regime variations within global models. At Umiujaq, a dense network of past and current observational sites exists. There, we have collected site descriptions for all sites known to already have homogenous metadata (e.g. SILA sites) and we have installed additional temperature measurements in vertical and horizontal previously un-sampled rock surfaces (Figure 4).

Mapping snow cover and active layer variations at the Bylot island research station

Active layer development is tightly linked to landscape hydrology and vegetation, and in order to better anticipate the impact of current changes on high arctic tundra (e.g. thermokarst or shrubification) a new project quantifying snow-vegetation-permafrost interactions was launched at Bylot Island (Nunavut) with the collaboration of cold region hydrologist Christophe Kinnard from UQTR. Spatial snow distribution was assessed in May 2016 (will be repeated in 2017) with repeat photography and point measurements. The results will be combined with existing long-term data and upcoming UAV-based snow maps in order to study the spatio-temporal evolution of the snow cover and its impact on slope hydrology, soil temperature, and vegetation type and phenology (MSc Matthieu Loyer). The long-term climate sensitivity of the snow cover and coupled soil thermal and moisture regimes will be assessed using simulations with a physically based-model and published climate change scenarios (PhD to be recruited). Forcing and validating data will rely on available long-term observations from the SILA network (snow surveys, ground temperature and moisture). In addition, detailed observations collected since 2016 at 100 points in five vegetation types on a mesic slope (including vegetation and top soil characterization, near-surface temperature, thaw depth and soil moisture) and at two sites in a water-track will provide measured data for the modelling work.

Mapping and assessing the impacts of tundra shrubification on permafrost terrain in the Low Arctic and the Sub-Arctic

Landscape transformation associated with current environmental change includes marked increase in shrub cover especially in the Low Arctic (Myers-Smith et al. 2011) where it alters snow distribution (Paradis et al. 2016) and reduces berry productivity (MSc Lussier, Henry et al. ArcticNet project). The impact on permafrost temperature regime is very large through coeval changes in snow cover duration, depth and

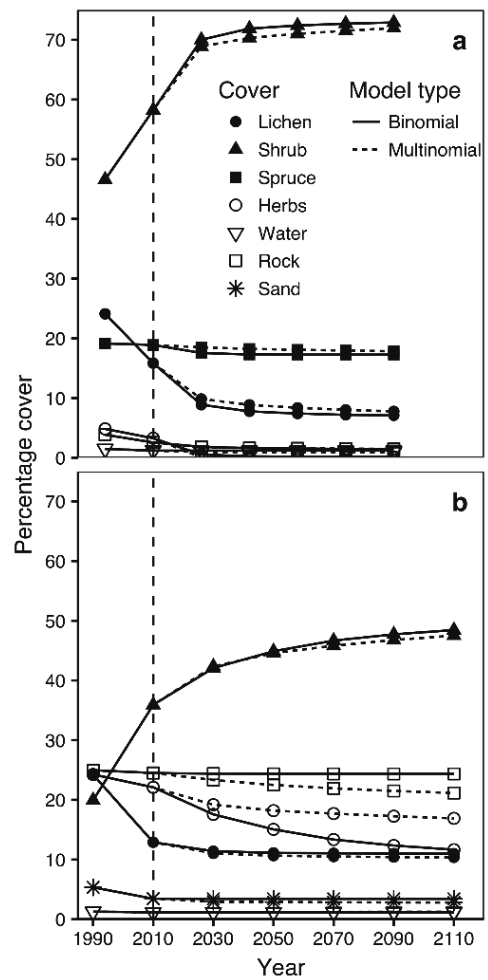


Figure 5. Percentage of shrub cover change modeled atUmiujaq.

density structure in winter and through surface albedo and soil humidity changes in summer. The permafrost-snow-vegetation relationship is now at the core of concerns in climate change science. MSc student Marc-André Lemay adopted a land cover change modelling approach in order to identify variables driving shrub cover increase near Umiujaq, in Nunavik (Subarctic Québec). Using land cover maps from 1990/1994 and 2010 and a LiDAR-derived DEM, he modelled observed changes using two competing approaches: binomial modelling of transitions to shrub dominance and multinomial modelling of all possible land cover transitions. His models were used to generate spatially

Figure 6. Wedge complex (left panel) and up-growth forms of ice wedges observed in 1990-1991 curently melting (rigth panel).

explicit predictions of transition to shrub dominance in the near future as well as long-term predictions of the proportion of different land cover types. Variables that changed with the spatial configuration of the data (e.g. surrounding and shrub edge) were computed after each time step to take into account the new spatial configuration of land cover (Figure 5). He found that shrubs tended to colonize more readily low-elevation areas and moderate slopes, while their cover was more likely to increase in the surrounding of existing shrub patches. The predicted probabilities of shrub increase in the region were consistent with patterns of change inferred from field data, but not from recent increases in NDVI. These findings increase the current understanding of the factors driving shrubification, while warranting further research on its impacts on ecosystem function and the link between land cover changes and variations in remotely sensed vegetation indices.

Assessing the impact of 25 years of climate warming on active layer and ice wedge dynamics in Narsajuaq near Salluit, Nunavik

One month of fieldwork in the Narsajuaq valley at the head of Sugluk fjord was dedicated by Ph. D. student Samuel Gagnon and his assistants to mapping vegetation and morphological changes since 1958 (year of the first aerial photographs) and 1991 (year of field work for a previous Ph. D. thesis on ice wedges in permafrost; Kasper and Allard, 2001). Using technologies such as remote sensing (acquired high satellite resolution image in July), a new automated meteorological station, thermistor cables, snow cover sensor and revisiting field survey sites of 1990-1991 now allow to make direct observations of environmental changes over the past 27 years. This comes after the inception of climate warming in 1993 in Nunavik after decades of climate cooling and activation of ice wedge cracking. Since then the climate has warmed by 3 °C.

Our preliminary results show that most ice wedges do not crack anymore in the study area. Although the active layer increased by more than 200% (from about 25 cm to 60 cm in organic-rich soils), the ice-wedges have not begun to thaw yet at depth however, contrary to what is currently reported elsewhere in the international literature. Rather, the up growth forms of ice wedges observed in 1990-1991 are melting, leaving the main wedges still intact deeper in the ground (Figure 6 left and right panels). Tunnels are left in the active layer where some ice wedge tops were present, allowing subsurface for air and water flow in conduits. Vegetation surveys in August 2016 suggest that mosses and peatlands have expanded and gotten thicker during the 27 year interval over the low center polygons and the furrows over ice wedges, therefore likely slowing the warming of the ground by providing some insulation.

Precise mapping of the furrows, of new and vanished lakes, peatland extent, new shrub growth and erosion landforms is underway. Thermal and climate data will be retrieved in August 2017.

The final aim is to understand all the components of the changing system with their influence on the ground temperature regime and the relative equilibrium of permafrost. The community of Salluit manifested great interest in the study and its outcomes.

2. Permafrost knowledge transfer and technical support to communities.

Hazards Mapping Project and permafrost and infrastructure monitoring in Old Crow, YT

This project mapped hazard risks at the Arctic community of Old Crow, YT, located inland near the Old Crow Flats. Delivered in April 2016, this hazard map is intended to serve as an adaptation planning tool and supports responsible, forward-looking decisions related to climate change impacts on the community. The map integrates landscape hazards related to permafrost, surficial geology and hydrology. It also considers potential future risks in response to changes in climate.

The work was accomplished by gathering and mapping geoscience data in the community, including information about local climate, geology, permafrost, and hydrology. Projections of future climate variability are used to identify potential future trajectories of change. The research team uses the geoscience data to rank hazard risks, and creates a map showing hazard risks using stoplight colours. By incorporating projections of future climate variability, the hazard map reflects both current and potential future conditions.

The hazard map will used by the First Nations as part of the adaptation planning process, and shall also be useful for engineers, planners, consultants, and all levels of governmental and non-governmental decision-makers.

Natural hazards evaluation and mapping in six communities of Nunavik

Under phase 1 of a project with the Ministère de la Sécurité Publique du Québec (MSP) to assess the vulnerability of Nunavik communities to natural hazards and the potentially increased risk of their increased occurrence under climate warming, six communities were fully documented: Inukjuak, Puvirnituq, Ivujivik, Kangiqsujjuaq, Quaqtaq and Kangiqsualujjuaq. The methodology involves an inventory of every single building, services and particularly strategic infrastructure such as airports, water intake and distribution facilities, sewage facilities, power plants and potential shelter buildings. All potential hazards, were considered either geomorphological or climatically driven, from avalanches to inundations and encompassing thermokarst and landslides. The risk evaluation approach is based on the probability of occurrence/recurrence, the level of potential impacts and the duration and spatial scale of the impacts. For each community the evaluated risks of hazards are presented in a matrix and the potentially affected areas or infrastructures are presented on map. Figure 7 shows the risk assessment map for Inukjuak.

Those risk assessment maps are a new layer of information above the previously produced GIS portfolio of maps of surficial geology, permafrost conditions and potential for construction. They are intended to support land use planning and raise the level of readiness of the emergency services.

Permafrost thaw, food security and traditional activities: Impacts on Jean Marie River First Nation, NWT - Permafrost as a possible source of mercury contamination

Jean Marie River First Nation (JMRFN), located 127 km east of Fort Simpson, is a very active

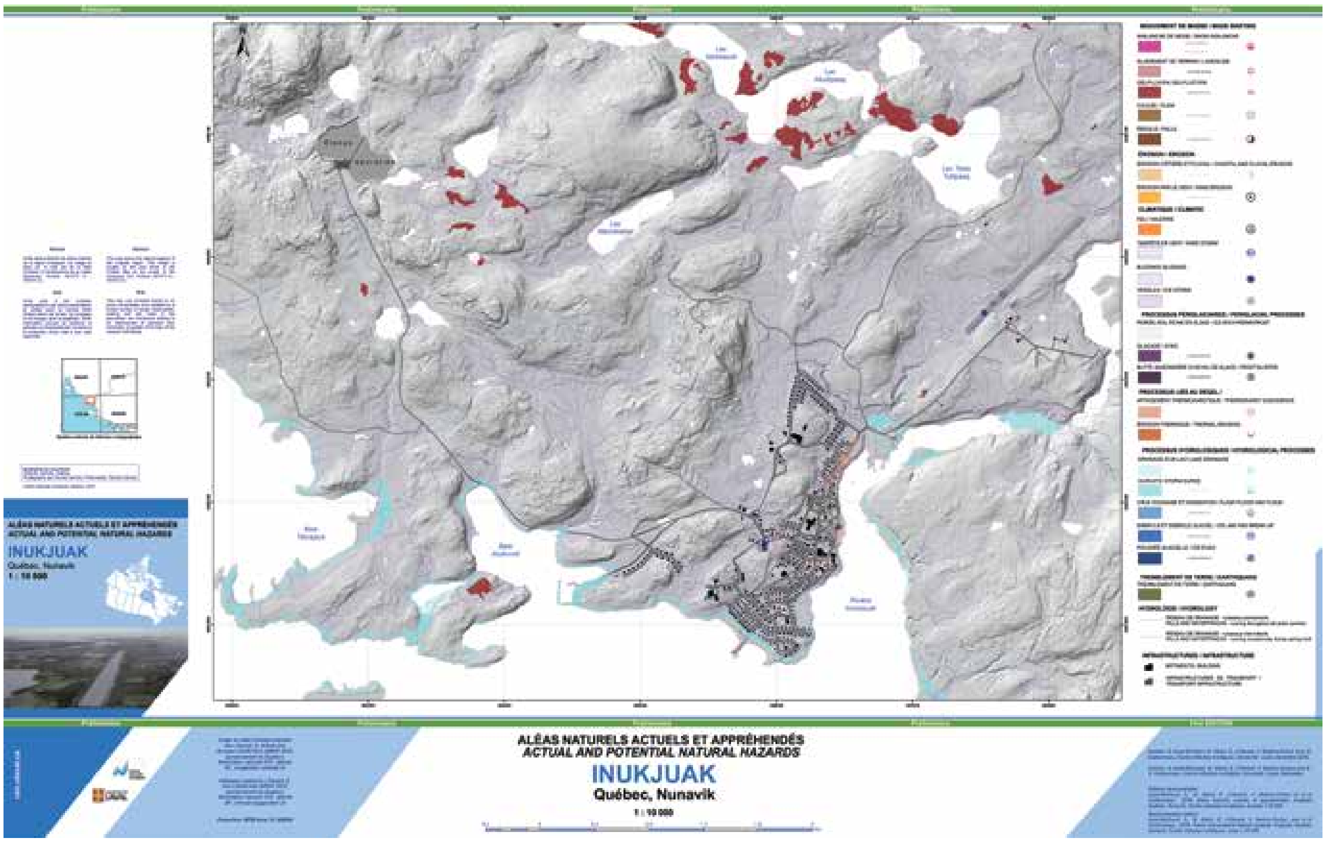


Figure 7. Risk assessment map for Inukjuak.

community that has led and participated in many scientific and traditional knowledge studies in the past few years. Currently, two primary community concerns are the impacts of climate change on country food supply and the contamination of some of their food by heavy metals. The community has already taken measures to have a better understanding of the local impacts of these two concerns; it also has initiated several climate change studies including two that are studying the vulnerability of the land to permafrost thawing and its relation to country food supplies.

Tracing the Origin of Mercury Contamination in the Lakes and Fish of the Jean Marie River First Nation Lands

JRMFN knows that the water and the fish of certain lakes, such as Ekali Lake (10V 628692 6797653), are contaminated by mercury to a point where it is a concern for human health. A large area made of frozen peatland is surrounding the north shore of the lake. One of the characteristics of this peaty soil is its potential for containing high concentrations of heavy metals, among them mercury. Researchers from NCE, in collaboration with University and private partners are now assisting with work to study permafrost as a potential source of mercury contamination of Ekali Lake. Mercury contamination could at least partially originate from the currently thawing peat. The community has a pressing need to understand what the source of the mercury contamination is and to locate non-contaminated lakes where it will be safe to go fishing. The focus of the project is to test permafrost for mercury content and to further explore whether degradation of permafrost provides a pathway for mercury to enter lakes and rivers.

The total mercury concentrations measured in the permafrost cores were between 4.4 and 77.8 ng/g, with an average of 20.6 ng/g, indicating that permafrost is a plausible contributor to the mercury contamination of the lakes. However, the magnitude of the contribution and the pathways and processes of the contaminations remain unclear. This will be the subject of another project proposed to NCP.

Final reporting of the first phase of the project was done in April 2016.

Changing Landscapes and Northern Ways of Life (formerly: The Human Dimensions of a Thawing Landscape), Jean Marie River, NWT, and Old Crow, YT

The Northern Climate ExChange and the University of Saskatchewan are working with the Jean Marie River First Nation and the Vuntut Gwitch'in First Nation to make climate change research relevant to northern Indigenous adaptation planning. The communities of Old Crow in Yukon and of Jean Marie River in NWT are both surrounded by permafrost and are dealing with the impacts of permafrost thaw. The "Human Dimensions of a Thawing Landscape" project combines data on landscape changes due to permafrost thawing, traditional land use, and climate change impacts to support community adaptation decision-making.

The project aims to answer the following questions:

- How can biophysical and social science products combine to meet the needs of northern Indigenous communities?
- How are the traditional land uses of the Jean Marie River First Nation and the Vuntut Gwitch'in First Nation impacted by climate change and thawing permafrost?

Students with the Yukon School of Visual Arts (SOVA) work with researchers, community members, local artists and Elders to communicate biophysical and social science research products, and traditional and local knowledge using electronic arts. Communities identify their concerns related to landscape thaw and choose a social science method to provide the framework for the adaptation planning process. Together the community and researchers are co-developing a process for incorporating traditional knowledge, western science and current community priorities into northern Indigenous community planning.

In the first year of the project we held our first workshop in Dawson City, Yukon with representatives from the two communities. From each community, a Community Coordinator, an Artist, and at least one Elder attended the four-day workshop. Also attending were four art students from the Yukon School of Visual Arts, and researchers from the University of Saskatchewan, Yukon School of Visual Arts, and Yukon College.

At the workshop presentations were made on topics as varied as permafrost and landscape change, arts, social science methods, and the concerns of the two communities. We also engaged in activities including art photography sessions and break out groups to discuss landscape change. Finally, we developed a plan for visits of the communities including lists of people to interview, as well as activities, landscapes and locations to photograph or put on video.

Following the workshop in Dawson City, the project team split into two groups that traveled to the two communities. In each of the communities the teams gathered photo, video and audio of landscape change, adaptation-related activities, ice break-up, animals, etc. In Old Crow three interviews were conducted with Elders. In Jean Marie River two interviews were conducted and four participants took part in a focus group. A community feast was held in both communities and the project team gave a presentation to community members on the project and the Dawson workshop.

Key activities:

1. Hired community coordinators in Jean Marie River, NWT (Margaret Ireland) and Old Crow, YT (Sophia Flather).

2. Held a planning workshop in Whitehorse.
3. Held an art/science workshop in Dawson City, Yukon.
4. Community visits to Old Crow and Jean Marie River to collect video/audio/photo data.
5. Presentations to communities.

3. Development of a teaching tool for Inuit and other stakeholders

Avativut

Allard et al. (Permafrost) and Henry et al. (Vegetation) ArcticNet projects are jointly contributing to the development of the Avativut Program in collaboration with the Kativik School Board (KSB) in Nunavik, as well as its training module, Avativut Mobile, also supported by Ouranos. Here we focus more on the Permafrost related activities.

Since the nomination of a new Director of Education Services at the Kativik School Board (KSB), several changes have been initiated. All the secondary language curriculums, including Science & Technology, are being reassessed and all research projects are put on hold. Therefore, the Permafrost LES has not been implemented in the classrooms this year despite the fact that all the educational material was ready. Moreover, the Berry and Ice LES were not on the 2016-2017 agenda as they are scheduled two years over a three-year cycle. Finally, the Berry and the Ice LES are actually being revisited as well.

Avativut Mobile

Two more teacher training workshops took place in Inukjuak and Umiujaq in March 2016, through the direct support of Ouranos and ArcticNet. These hands-on workshops helped the participants to better understand the scientific protocols, to better prepare for the activities, to be more confident in bringing their students on the land and to realize the importance of data entry. It also fostered more collaboration between the non-Inuit and the Inuit teachers. From these training sessions, we learned that Avativut LES are among the students' preferred ones and that Inuit teachers are showing a great interest in these activities. Some participants recommended to improve the interview kit, to produce more graphs from data and to develop tools for data entry and analysis (e.g. games).

PermaSim

Despite the context preventing the Permafrost LES to be implemented this year, the development of *PermaSim* was pursued. This educational software allows the user to view, interactively, changes to the ground thermal regime over a one-year period in communities in Nunavik. We have partnered with the Ouranos Consortium to model the air temperatures for the 13 Nunavik communities with permafrost for three periods: 1995-2015, 2040-2060 and 2080-2099. Climate models were used to simulate moderate (INM-CM4) and high (CanESM2) warming hypotheses. From these data, temperatures in the permafrost are modelled daily for five soil types (clay, silt, sand, rock, peat moss), four plant covers (high shrubs, low shrubs, lichen, none), and a depth up to 5 m. The users have the possibility to generate animated graphs and to save graphs with different parameters to facilitate comparisons. *PermaSim* has enormous potential as a tool for teaching and understanding permafrost dynamics. The development of a mobile application for *PermaSim* (iPad, smartphone) is planned for 2017. Figure 8 shows a screen capture of the *PermaSim* software with modeled air and soil temperatures for 1995-2015, 2040-2060 and 2080-2099 time periods.

Automated graphs

A graphing tool was from the berry database to produce automated graphs. This type of application will also be useful to illustrate other datasets, for example ice onset and breakup dates, ice thickness or permafrost active layer depth.

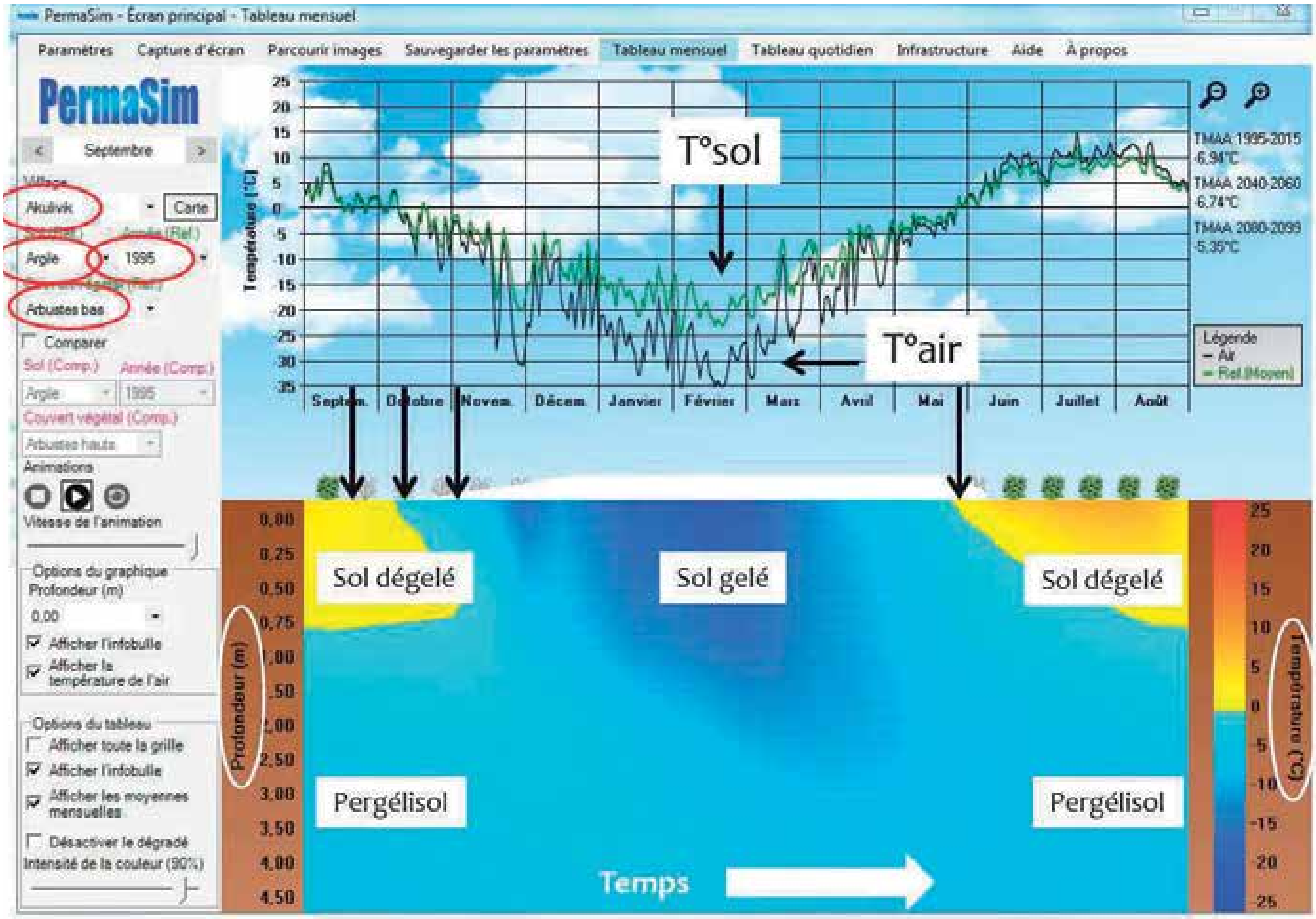


Figure 8. Example of the PermaSim simulation tool.

Outreach

Outreach posters were created in collaboration with a graphic designer to visually explain the Avativut Program's general objectives, values and philosophy. The posters will be distributed in all Nunavik schools before the end of March 2017.

4. Support of infrastructure renovation and construction

Adapting the northern section of the Alaska Highway

From 2012 to 2015, the Northern Climate ExChange (NCE) of Yukon has partnered with the Highways and Public Works of Yukon (HPW) to develop a field guide to inform climate change adaptation along the northern 200 km of the Alaska Highway from Burwash Landing to the Yukon/Alaska border.

The project examined the potential sensitivity of the permafrost along the highway to present and future climate variability. To conduct this project, the project team used geophysical data, geotechnical reports, highway maintenance records, air photos, and other readily available data sources, combined them with field investigations to identify thaw-sensitive permafrost areas underlying the highway. The field investigation was a multi-disciplinary approach that included permafrost coring, geocryological analyses, ground temperature and climate monitoring, Electrical Resistivity Tomography (ERT), and remote sensing techniques.

Findings culminated in the development of a permafrost thaw sensitivity vulnerability map. Projections of future climate scenarios were used to examine potential climate change impacts. Results indicated that the regional glacial history has influenced permafrost distribution and characteristics. Soils underlain by permafrost located within a few square kilometers of each other exhibit a wide range of ages, ground temperatures, thicknesses, and ground ice content and nature.

While located in an extensive discontinuous permafrost zone, this section of the Alaska Highway is almost completely built on permafrost. Less than 20% of the road is located on ground that has a low vulnerability to permafrost thaw and the remaining 80% is on moderately to highly vulnerable areas.

The resulting product of the survey is a field guide that is used by HPW to facilitate the development of appropriate maintenance and remediation strategies, ensuring the highway's continued viability.

In 2016, activities in this project consisted in finalizing the remediation designs for four selected sites, and final reporting.

<u>Planning a permafrost-resilient fibre optic link to Inuvik</u>

In cold climates such as central and northern Yukon, construction at a site must account for permafrost characteristics and implement design adaptations to ensure the resilience of the infrastructure, or risk costly repairs and interruption to services. The proposed fibre optic link from Inuvik to Dawson City will cross a vast area of permafrost. The challenges associated with construction of this line will be compounded because the cable is buried and because the infrastructure crosses hundreds of kilometres of terrain where little is known about permafrost conditions. Existing highway infrastructure in the region is already affected by permafrost degradation. A buried fibre optic cable may be exposed to numerous permafrost-related hazards in this region such as:

- thermokarst processes resulting in ground subsidence and the formation of depressions and uneven surfaces;
- thermal contraction and cracking of the ground due to large, rapid and differential temperature variations;
- mass movement triggered by seasonal freeze and thaw of the active layer and extreme events linked to permafrost thaw.

Several levels of assessment of problematic areas associated with permafrost are required in order to plan, cost, design and build a route of least vulnerability. Recognizing this, NorthwestTel (NWTel) and Ledcor have sought information that will inform their design basis for the Canada North Fibre Loop. This memo and associated maps were produced by Palmer Environmental Consulting Group (PECG) and Northern Climate ExChange (NCE) in order to provide NWTel and Ledcor with a preliminary understanding of the distribution and characteristics of permafrost and related terrain sensitivity along the Dempster Highway right-of-way. This insight will help NWTel and Ledcor account for permafrost conditions and sensitivities in their initial estimates of construction and maintenance costs for the fibre optic line.

This was a desktop-based preliminary assessment of permafrost conditions that took full advantage of the team's familiarity with the terrain characteristics, permafrost conditions and related geohazards in both glaciated and unglaciated settings of central to northern Yukon. The tasks performed in this project address potential ground movement linked to changes in permafrost conditions in response to ground disturbances and climate change.

The preliminary assessment of permafrost and mass movement geohazard conditions was completed through three main tasks:

Task 1 – Preliminary Mapping and Characterization of Permafrost;

Task 2 – Mass Movement Geohazard Mapping;

Task 3 – Final Mapping and Technical Reporting.

The tasks above were completed without fieldwork.

Investigating the origin of Sink holes at km 82 and 103 of the Dempster Highway

The Dempster Highway is the only road connection to the western Arctic, and when the Inuvik-Tuktoyaktuk Highway is completed, it will be part of the infrastructure linking southern Canada with the Arctic Ocean. Extensive reconstruction of the highway was completed on the NWT side of the territorial border in response to degradation of the road surface and embankment. Upgrading of roads to year-round availability is required in some parts of Yukon in response to demand from the mining industry as mineral development accelerates in the territory. A number of sink holes are developing along the southern part of the Demspter Highway. Suspected causes of this are permafrost degradation or water movement within the road embankment. NCE and Highways and Public Works aim to understand and, as much as possible, remediate the issues caused by the formation of sink holes at km 82 of the Dempster Highway and a site near Two Moose Lake where thermokarst is impacting the road.

The project team reviewed existing data and reports from previous surveys and studies pertaining to the study area and its surroundings. Additional information such as air photos, satellite imagery, and surficial geological maps are used to gain insight about the geomorphologic and surficial geologic conditions of the area.

The field assessment focused on the foot of the embankment and the field area adjacent to the embankment on both sides of the road. A light and portable GOLZ Earth-drill system was used to drill a shallow borehole at km 103, in the field, down to 3.16 m. Permafrost samples were collected. After a summary description, each sample extracted from the borehole were put in polybags and sealed. The still-frozen samples were kept frozen and taken back to the laboratory for further analyses. The borehole was instrument with a 4-channel Hobo Logger recording temperature at 0, 0.5, 1.5, 3.16 m depths.

At km 82, an existing borehole that had previously been instrumented with ground temperature monitoring loggers by HPW was inspected and repaired (some wires had been damaged). An Abem Terrameter LS system was used to perform electrical resistivity tomography (ERT) surveys (Figure 9). It consists of a four-channel imaging unit and four electrode cables, each with 20 take-outs at five-metre intervals. To conduct a survey, 81 electrodes were driven into the ground along a survey line and connected to the electrode cables. A direct current electrical pulse is sent from the resistivity meter along the survey line. The resulting data consists of a cross-sectional (2D) plot of the ground's resistivity (Ω.m) versus depth (m) for the length of the survey. A total of seven ERT surveys were done:

Km 82: three (3) 200 m–long survey lines with three different array setups each, including Wenner, Dipole-Dipole, and Gradient, for a total of nine surveys: in the field at the right-hand side of the road, and at the toe of the embankment and in the field at the left-hand side of the road.

Km 103: Two Moose Lake: four (4) 200 m–long survey lines with three different array setups each, including Wenner, Dipole-Dipole, and Gradient, for a total of 12 surveys: one in the field at the right-hand side of the road, and two at the toe of the embankment and one in the field at the left-hand side of the road.

Results of the surveys were post-treated and analyzed at the NCE using inversion software Res2Dlnv 64.

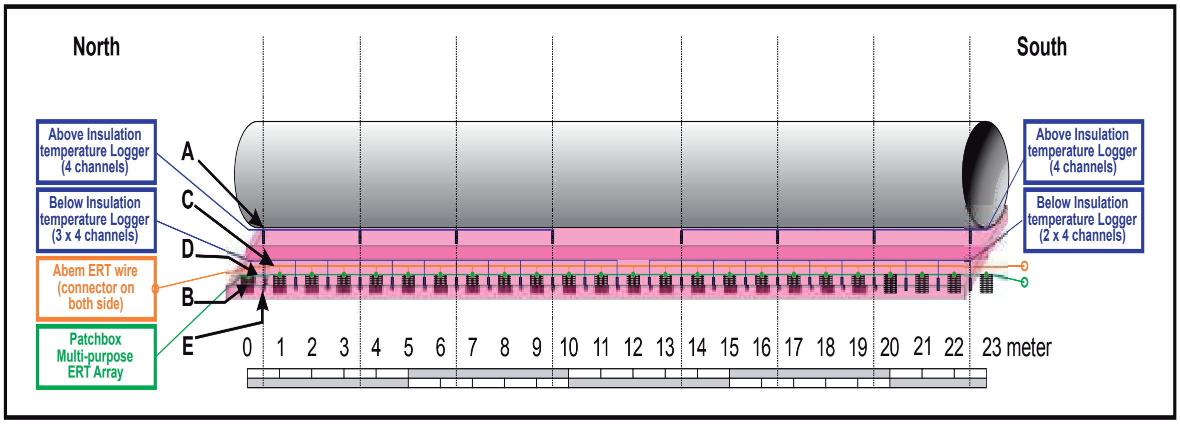


Figure 9. Scheme of the Abem Terrameter LS system used in the electrical resistivity tomography (ERT) surveys.

At the laboratory, the permafrost cores was cleaned and photographed and then thoroughly described. Laboratory analyses were carried out to measure the properties of the permafrost samples. Both soil grain characteristics and ice characteristics were evaluated. A grain-size analysis was performed on selected samples. To evaluate ice characteristics in permafrost samples, the cryostructure, volumetric ice content and gravimetric ice content where quantified. These analyses should provide information such as soil genesis, climate conditions at the time of freezing, permafrost development history, and ground vulnerability when permafrost degrades. A log will be created by assembling laboratory photos of the cores. The Borehole log includes maximal depths, grain size ratio and volumetric ice content. ERT surveys are in the process of being interpreted in function of the geomorphological context and of the findings of the borehole and ground temperature investigations.

The interpretation of the results and writing of a report will be carried out during winter 2017.

Development of a climate-resilient functional plan for the Dempster Highway

Beginning in September 2016, this project will develop a climate-resilient functional plan for Yukon's Dempster Highway corridor. The project moves beyond the typical functional plan process by integrating climate change and geohazards research, industry expertise, and adaptation strategies into the planning process. The project scope was developed collaboratively between the Yukon Research Centre and Highways and Public Works; it is designed with a holistic approach to highway planning. As such, work components are scheduled to facilitate exchange of ideas in support of both research focus and functional plan progress. The research and analysis required to assess climate and geohazard vulnerability are be carried out by the Northern Climate ExChange, part of the Yukon Research Centre at Yukon College, and a consultant will carry out the functional planning process. Project and study objectives include development of a function plan that considers climate change and incorporates climate resiliency into short, medium and long term planning and cost estimates. The final plan will incorporate industry-identified innovation opportunities and stimulate partnerships between industry, research, and Highways and Public Works with the goal of building practical adaptation strategies. Products of this project will include a state of the highway report, a report summarizing climate- and geohazard-related vulnerabilities for the highway corridor, a functional plan that incorporates climate change, and an industry innovation workshop.

This project proposes an innovative approach to creating a functional plan in a region where climate change impacts are already apparent and are expected to continue or even accelerate. Importantly, few (if any) other planning processes in the region are integrating climate change considerations directly in a way that is comparable to what is proposed in this project. We are ensuring that the future costs associated with the maintenance of transportation infrastructure takes potential climate change impacts into account.

A two-day field pre-fieldwork visit took place at the end of August 2016 with team members of the NCE and HPW. Local road manager from HPW joined the team and travelled the 465 km Yukon Dempster highway section. Observations were done and site presenting road issues related or unrelated to permafrost thaw where identified. Based on the visit some sites where selected for field investigation.

Field investigation occurred in October 2016, and consisted mostly in ERT surveying. A 200 m-long ERT survey was made at km 116.5, km 124, km 126, and km 192. For each site, two types of arrays were used: Wenner and Dipole-Dipole. Results of the surveys were post-treated and analyzed at the NCE using inversion software Res2Dlnv 64.

Additional fieldwork including ERT survey and permafrost sampling will be carried out in Spring 2017 as the project continues.

ERT and temperature monitoring to assess the effectiveness of insulated culverts

The movement of surface water across linear infrastructure (e.g., highways, airstrips, etc.) has always been a challenging issue in permafrost areas. Channeling runoff through culverts is the most common solution to manage surface water. The drawback of this approach is that it creates a "hot spot" at the culvert location whereby water transfers heat to the ground. Localized subsidence may occur causing disruption of the infrastructure and shortening its useful life. Officials at Yukon Government's Department of Highways and Public Works (HPW) are eager to mitigate such issues, especially along the Dempster Highway, where multiple culvert failures resulted from permafrost thaw. Repairs or replacement of the culverts causes substantial costs, and HPW is eager to better understand the impact of the culverts on permafrost and to test the effectiveness of the methods used to maintain permafrost stability. This project will take advantage of the opportunity offered by the reconstruction of a culvert at km 381 of the Dempster Highway to monitor the impact of the culvert on permafrost, and to evaluate the effectiveness of remediation techniques through an innovative approach combining temperature and electrical resistivity monitoring.

The project has two main objectives:

1. to monitor the impact of the culvert on underlying permafrost using a combination of temperature monitoring and electrical resistivity tomography (ERT), and
2. to assess the effectiveness of an insulating layer installed below the culvert through temperature monitoring.

Results of the study will allow HPW to monitor permafrost conditions under the culvert using a non-invasive and cost-effective approach applicable throughout their highway network. The information provided by the study will allow HPW to adjust and perfect their approaches, and will be applicable at other permafrost areas in Yukon as well as in elsewhere in the North.

The activities in this project include:

- Characterization of permafrost at the site of the km 381 culvert using active layer probing, water jet drilling, and electrical resistivity tomography (ERT), as applicable.
- Installation of temperature monitoring sensors and an array of ERT cables directly below the insulation

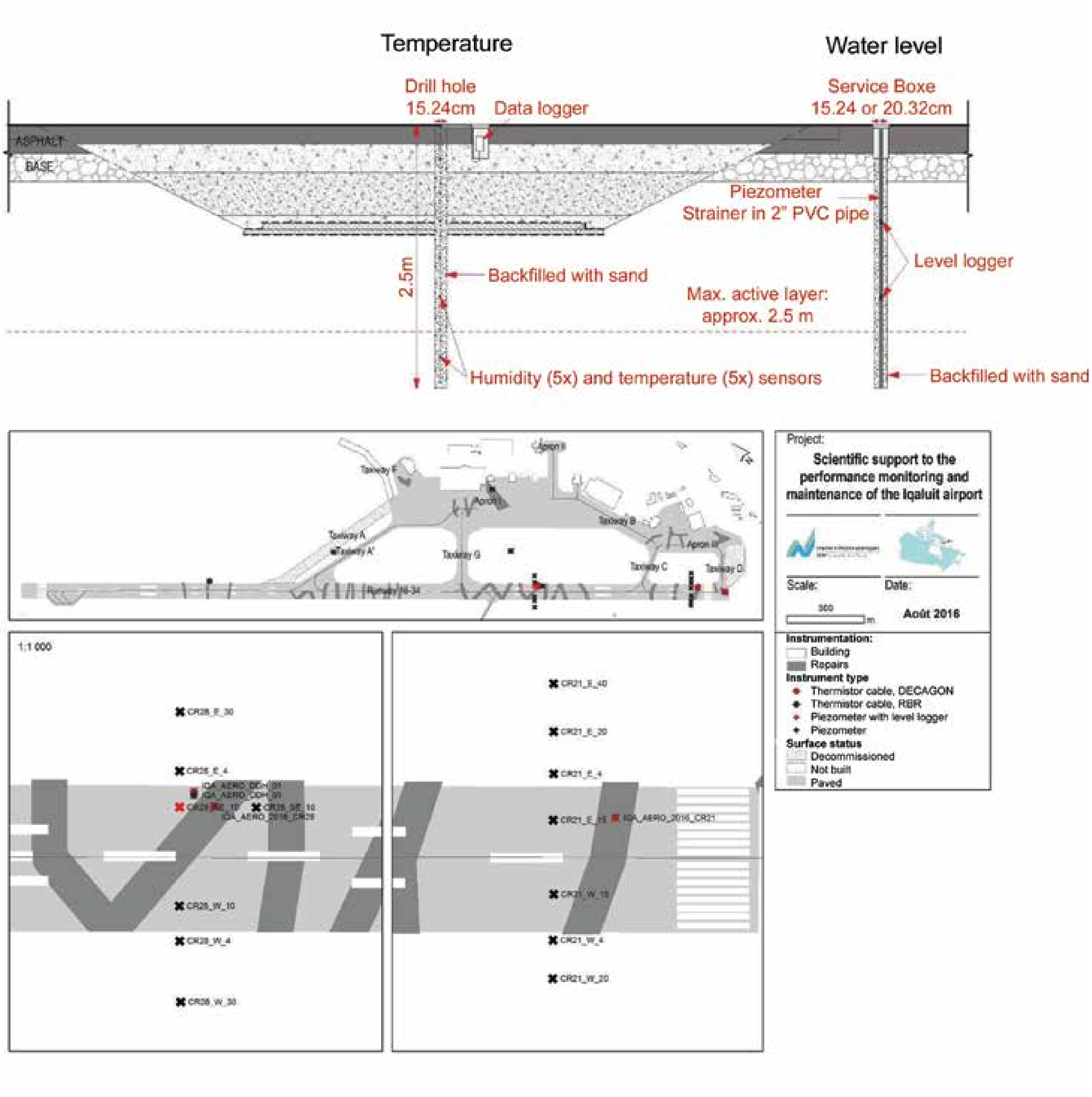


Figure 10. Thermistor cables installed in repaired cracks across the runway in Iqaluit.

layer buried under the culvert. Temperature sensors are also buried above the insulation.

- Data retrieval from the site of the culvert and analysis of the data.

The monitoring array was designed in August 2016 in the NCE Laboratory facility. It consists of a 24-electrode ERT monitoring array, with one temperature sensor located between each electrode (total: 23 sensors), located in natural ground just below the insulating layer, and an eight-sensor temperature monitoring array located between the insulating layer and the culvert.

Airports: Iqaluit, Kujjuaq and other Nunavik airports

In Iqaluit, our team collaborated with Arctic Infrastructure Partners (AIP), the consortium mandated for upgrading and operating the airport. Summer 2016 was busy mostly for repairing wide (often more than 1 m) linear furrows along frost cracks in the runway. Most cracks and furrows lie above ice-wedges that have been thawing recently. The contractor opened ditches along them down to the permafrost, installed an insulation layer, refilled, and compacted the fill. Finally, new pavement was put on top. Thermistor cables were installed in those repaired cracks by drilling from the surface through the insulation and down into the underlying permafrost (Figure 10a). They will monitor the performance of these "adaptation" solutions to the problem of ice-wedge thawing. In addition, arrays of three wells each were also installed at two emplacements across the runway (on the sides and in the center line) to monitor both temperature and water table depth in the active layer (Figure 10b). The intent is to monitor the impact of the perched water table that gets trapped due to faster active layer thaw beneath the pavement than under the unpaved shoulders because of albedo differences. A high water table may impact strength of the runway surface; it could also change the temperature and the freezing-thawing regime of the active layer under the runway through latent heat effects, with long term consequences on permafrost stability.

The stability of the infrastructure surface will remain sensitive to further climate warming and, particularly, to warmer than normal summers. Therefore the risk to the runway surface's operational capacity associated with fast climate warming or exceptional warm summers is a concern for the coming years.

We also proposed making a ditch along the newly built taxiway-A to prevent water infiltration under the pavement and, particularly, along ice wedges that run across the taxiway. The ditch was terminated by AIP in September. Close collaboration is maintained with AIP and its partnering contractors for providing the necessary permafrost data and mathematical models for performance monitoring for the coming years of operation. Renewed funding has been requested from Transport Canada for this project in December 2016.

In Kuujjuaq, the maintenance of our instrumentation under the paved runway 07-25 was carried on. The retrieved data were compiled and analysed. The key issue is here again the drainage of the perched water table in the active layer that is monitored in wells in the runways and with soil water measurement devices in the soil alongside. The results show that the French drains (tranchées drainantes) installed by Transports Canada efficiently drain water surpluses under the runway after major rain events, with a positive impact on the bearing capacity of the runway and the thermal regime of the foundation soils.

Elsewhere in Nunavik, we have been monitoring again in 2016 the thermal performance of adaptation measures that were implemented since 2012 at various airports and access roads under a long term program with Ministère des Transports du Québec (MTQ). Those engineering measures had been designed based on our previous characterization work of the late 2000s. The modified airports are Salluit (truncated gentle slope side of embankment), the Salluit access road (heat drain embankment monitored with fiber optics distributed temperature sensing), Quaqtaq (truncated slope + new ditch system), Tasiujaq (various embankment sides) and Puvirnituq (air convection berm). Our team got experience in repairing broken fiber optics through our maintenance operations along the Salluit road.

One major observation stemming out of this long term monitoring is the extreme importance of inter-annual climate variability for the stability of roads and runways. For instance, while the extremely warm summer of 2010 in northeastern Canada had impacts by having the active layer at greater depths, the colder years of 2014-2015 have brought back the active layer base at shallower depths and helped maintain the permafrost table within embankments. Modelling is planned to better discriminate between the true performance of the adaptive engineering designs and the thermal control of climate variations.

Development of a risk analysis tool for managing transportation infrastructure on permafrost

The goal of this project is to create tools for the management and design of existing and new infrastructure in permafrost areas.

During 2016, the project included an additional literature review on select permafrost dangers, conducting statistical analyses of permafrost geotechnical information, investigating the mechanics of inter-embankment bridging due to ice-wedge melting through detailed literature review and laboratory testing, and reviewing the available literature for the development of statistically valid spatial permafrost analyses. Due to this work, the dangers to be included within the project's resulting software are: structural failure of culverts, settlement (total and differential), bridging (via soil particle position), and active layer detachment landslides.

During the review of the variability of permafrost geotechnical index properties, little existing information has been discovered. Thus, the information found in three databases of geotechnical

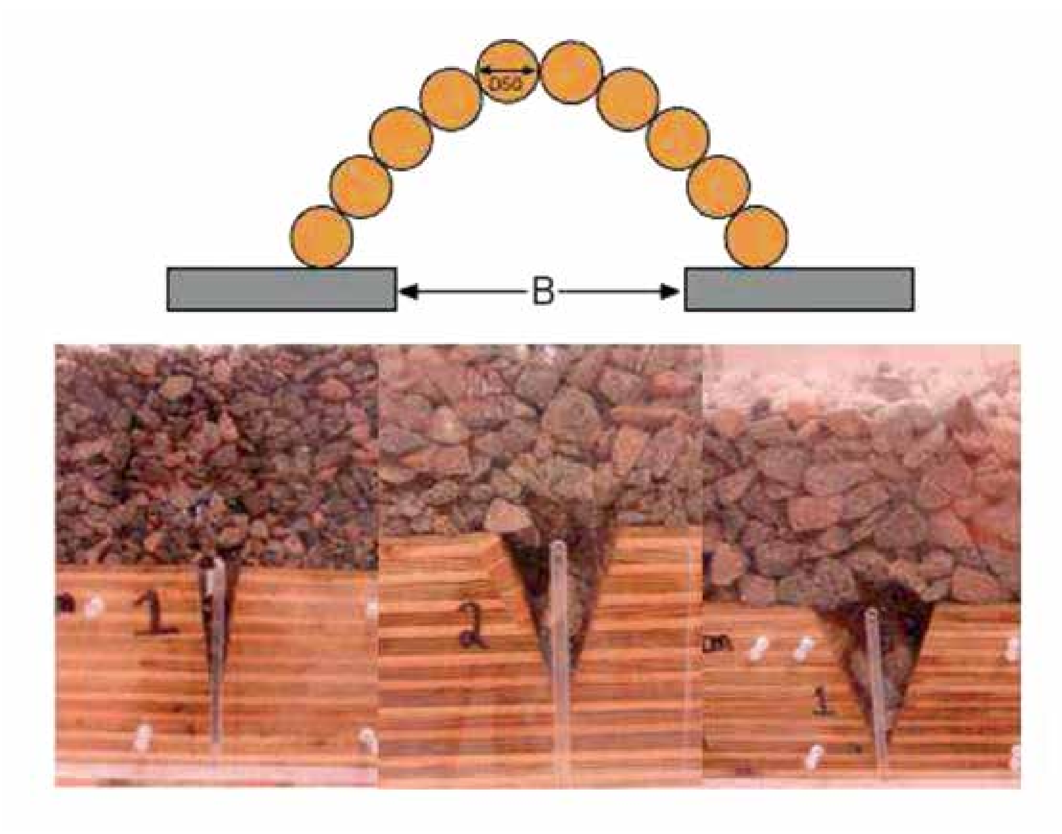


Figure 11. Soil particle bridging sketch and laboratory testing photos. Note the definition of bridging ratio is the width of gap (B).

index tests from the Geological Survey of Canada has been used to develop variability statistics for moisture content, bulk density, specific gravity and plasticity parameters for permafrost soils within the Mackenzie River Delta. A paper presenting and discussing this work is currently under internal university review and a poster was presented at the 2016 ArcticNet ASM.

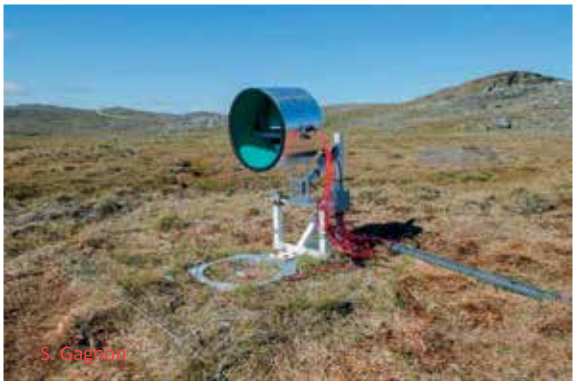
As noted in our 2015 report, there is a lack of information with regard to the mechanics of bridging over voids made by ground ice melting under embankments. Three possible mechanisms were investigated: bridging via soil particle position; negative pore pressures due to interface suction (unsaturated soil mechanics) and flexure of frozen soils within the embankment. Full scale laboratory testing was conducted in the civil engineering facility at Laval University to determine the probabilities of bridging occurrence as a function of the bridging ratio (gap bridged to average soil particle size) (Figure 11). The testing confirmed the ratios observed within the literature. A literature review combined with structural flexure mechanics allowed the development of limit state equations for the stability of bridges via interparticle bonding (frozen soils) or suction (unsaturated soil mechanics). A paper presenting and discussing the results of this work is also under internal university review and an oral presentation was presented at the 2016 ArcticNet Annual Scientific Meeting.

The final goals for the computer program for risk analysis were also developed in 2016. These include the final dangers (presented above), the analysis of consequences, evaluation of risk and a fragility assessment for a warming climate based on arbitrary increases in the mean annual air temperature at a site. The danger's hazard will be calculated using Monte Carlo Simulation or First Order Second Moment (FOSM) analysis methods from user input, including geotechnical, climate and permafrost information, and infrastructure failure criteria. Consequences will be calculated via direct costs (engineering design, material, labor and equipment) with applied factors (subjective scalar factors) for social impacts from closure or injuries/fatalities on the surrounding communities. The fragility analysis will allow forecasting of risk based on increases in mean annual air temperatures. The goals of the computer program were presented at the 2016 ArcticNet Annual Scientific Meeting and the 11th International Conference on Permafrost in Potsdam, Germany.

The work to date consists of steps for the creation and validation of a quantitative risk analysis tool. The next steps of the project involve its expansion to include the dangers discussed above, the consequence analysis, and air temperature fragility analysis. The program will be tested and validated in early 2017 with the excellent data acquired at the Iqaluit Airport, to determine the risk associated with thaw settlement and soil particle bridging, and a cost/benefit analysis analyzing the recent improvements to the airport. Additionally, the project will document the development of the tool, the applied statistical methods, limit state equations for the dangers and a user guide.

5. Development of innovative approaches and technologies

Ph.D student Samuel Gagnon and collaborators from our team designed a new model of automated chambers to detect and measure permafrost soil respiration (Figure 12). The new chambers allow to make continuous measurements of GHG emissions over long periods of time. They open and close over the studied soils with programmable automated electro-mechanical systems. They are fitted with low-cost sensors and open-source microcontrollers. Comparisons of the performance of the CO_2 sensor with a standard infrared gas analyzer (IRGA) were made. Compared to the IRGA, the sensor overestimated fluxes by only 6%, making it a good alternative to conventional devices to measure CO_2 concentrations. The chambers were compared to a commercial chamber (SRC-1, PP Systems) and results showed <15% discrepancy between the two types of chamber. These performances fall within the range of existing instrumentation as searched in the literature. This low-cost system shows high potential and



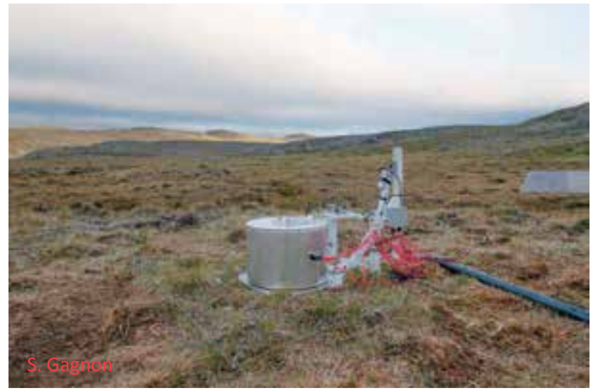


Figure 12. Automated chambers to detect and measure permafrost soil respiration.

represents a good alternative to existing methods and apparatuses to measure soil CO_2 emissions.

Follow-up on previous work

MSc student Marc-André Lemay completed his thesis (submitted November 2016) on spatially explicit modelling and prediction of shrub cover increase near Umiujaq, Nunavik. His work stemmed from ArcticNet supported studies that quantified shrub cover changes between 1990 and 2010 using aerial photo analyses (Provencher-Nolet et al. 2015). A number of publications were completed on the impacts of permafrost degradation on vegetation (Perreault et al. 2016 and Godin et al. 2016) and on vegetation-snow interactions (Paradis et al. 2016). MSc students Marilie Trudel and Maxime Tremblay are currently writing their theses.

Two papers originating from the ADAPT program are currently under review and two more are at the stage of final revisions.

New research project under Laval's Sentinel North program

NIs Allard, Doré and Calmels are key participants together with physicists and electrical engineers from the Centre d'Optique, Photonique et Lasers de l'Université Laval in a new Sentinel North project entitled Shining Light on Northern Communities: (SLiNC) networked sensor sentinels for real-time surveillance of infrastructures and ecosystems. The project targets interconnectivity of infrastructure monitoring systems for immediate benefit to northern communities and owners/operators of terrestrial transportation infrastructure. Construction, expansion, and land-use planning are required for economic development of a fast growing population in northern communities, yet they are troubled by climate change and destabilizing permafrost. Communication networks dedicated to monitoring ecosystems and infrastructures have the potential to provide tremendous capabilities: real-time observation of climate change impacts, hazard detection, early warning of risks, assessment of performance of applied adaptive designs, and enabling fast decision making to maintain infrastructure. Indeed, sensors are our primary sentinels of climate change. They are the arsenal of both applied researchers developing robust infrastructures (roads, airstrips, housing, etc.) and fundamental scientists studying the environment (meteorology, ecosystems, pollutants, etc.).

Sensors placed by Arctic villages under roads and airport runways produce results used by communities and owners to monitor climate change and address impacts. This data, and our close collaborative ties with stakeholders, provide the ground work for designing

and testing in real situations new, light-based, higher performance sensors, better adapted to northern operational conditions and, above all, interconnected in intelligent networks operating in real-time. Being able to link them into networks and feed real time databases and geographical information systems in support of decision making would bring more efficiency to monitoring and benefits to society. Hence the objectives of SLiNC are:

- Networking infrastructure-monitoring sensors (including early warning) in northern communities,
- Developing compact, wireless/fiber sensors for communities and remote data collection, and
- Developing low-power, wireless-enabled, fiber-optic linearly-distributed sensors for monitoring linear infrastructures such as roads and airport runways.

Needless to say, such networks and sensors developed for the monitoring of permafrost in human habitats and under infrastructures will be equally usable in natural terrain conditions for geological and hydrogeological monitoring, surface hydrology, periglacial process studies and ecological studies. But testing them first in Salluit, a community where a field research station and ancillary services exist, allows for easy access, tests, and on-site improvements. Similarly, we will run trials and adjustments of point and linear sensors in real road and runway conditions in collaboration with partners in the infrastructure business.

The total project's budget is $551k for the period 2017-2020.

DISCUSSION AND CONCLUSIONS

Project members have continued to address major issues in permafrost science that are relevant for the international efforts to increase understanding of permafrost and the environment. Progress was made in mapping permafrost and in assessing spatial variability of micro-climates and permafrost properties through local and regional field-based studies. The direct impacts of climate-vegetation-now cover changes on permafrost were documented in the field.

Through a series of project in Yukon, Nunavut, NWT and Nunavik, the research greatly supported the regional, provincial and federal governments in their efforts to develop new transportation infrastructure and find adaptive solutions to maintain the existing ones.

Community mapping of permafrost was less intense than in the previous years. This is likely due to the ending of sources of funding with changing governments. Communities still express their needs for such studies. However, hazard mapping and assessments to protect public safety and for planning emergency measures (if needed) were requested. In the same line of thought, risk analysis is being developed for managers and consultants to apply.

The teaching and training software *PermaSim* can actually be used by Northeners for assessing the impacts of climate change on their own community infrastructure.

Technological advances in 2016-2017 were mostly in the area of sensor-equipped chambers for measuring greenhouse gas emissions from tundra soils. The starting Sentinel North project is likely to be the launch pad of a new generation of sensing devices, data acquisition systems, electro-optical networks of data collecting and sharing in the domains of permafrost monitoring and socio-economic applications.

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EFFECTS OF CLIMATE SHIFTS ON THE CANADIAN ARCTIC WILDLIFE: ECOSYSTEM-BASED MONITORING AND MODELLING

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ABSTRACT

Arctic ecosystems are undergoing major changes related to climate shifts. An understanding of this transformation is critical to anticipating ways in which potential negative effects may be mitigated and positive ones may become beneficial. To achieve this, we propose four specific objectives. First, we will monitor about 35 wildlife populations (mostly mammals and birds) at 12 study sites across a large latitudinal gradient in the Eastern Canadian Arctic (IRIS 2 region, main sites: Rankin Inlet, Coats Island, Southampton Island, Igloolik Island, Bylot Island). Monitored components are distributed through all levels of the food web, from plants to predators, to give the best-possible picture of ecosystem changes. Second, we will carry out field observations and experiments to unravel important relations between wildlife and climate. This will enhance our understanding of ecological processes determining the response of wildlife to climate shifts. Third, we will identify (through modeling) the ecosystem-scale exposures and sensitivities of the tundra to climate change. This is a necessary step to reach our fourth objective, namely to estimate and map, at a regional scale, the ecological vulnerability of the tundra to climate shifts. We will use one region particularly exposed to climate change (Northern Quebec, IRIS 4 region) as a first case study to map tundra vulnerability, and will then expand this work to larger areas, such as the Canadian Arctic. Our efforts to upscale our research from the species to the ecosystem level will constitute a major legacy of our project beyond 2018. We work in collaboration with many partners including Environment Canada, Government of Nunavut, Canadian Wildlife Service, Parks Canada, Nunavut Tunngavik Inc., Nunavut and Nunavik Wildlife Management Boards, Baffinland Iron Mines Corporation, Agnico Eagle Mines Limited, Ouranos Consortium, and the Hunters and Trappers Organizations of many Northern communities. We will provide critical wildlife and ecosystem-related knowledge necessary to conduct the Integrated Regional Impact Studies of the “Eastern Arctic” and “Eastern Subarctic”, two of the four regions identified by ArcticNet for such assessments. While fostering strong ties and knowledge transfer with Inuit, our research will also provide training to a large number of Highly Qualified Personnel (including Northeners), who will then become uniquely positioned to meet the challenges arising from the rapid transformation of the North.

KEY MESSAGES

- Technological progress is revolutionizing wildlife research and we have participated to this in 2016: we have tracked several northern wildlife species with miniaturized satellite loggers, we wrote the script FoxMask that can recognize and count animals from pictures, we monitored automatically bird nests with tiny tags to register parental presence, and we recorded sounds of the tundra to study species from their auditory signals.
- We have demonstrated during 2016 that in winter, snowy owls are more abundant in Southern Canada following summers of high lemming abundance.
- We found strong links between migratory connectivity and population declines in shorebirds, such as in the semipalmated sandpiper, the species with the strongest decline.
- We showed that individuals and populations of the same species can vary in their responses to climate variation. Detecting and accounting for inter- and intra-population heterogeneity will improve demographic modelling and population viability analyses.
- We developed throughout 2016 the international research network ArcticWEB (http://arcticweb-project.org/index.html), allowing us to conduct simultaneous, circumpolar ecological observations and experiments in terrestrial arctic ecology.
- We got in 2016 the first outputs of our modeling of the vulnerability of the tundra of Nunavik. A borealisation of the northern tip of the Ungava Peninsula is clearly underway.

OBJECTIVES

1. To monitor about 35 wildlife populations across multiple trophic levels (from plants to predators) at 12 study sites spanning a large latitudinal and temperature gradient in the eastern Canadian Arctic.
2. To better understand six key processes linking climate shifts to wildlife population dynamics and species interactions.
3. To identify, through modeling, the ecosystem-scale exposures and sensitivities of the tundra to climate change.
4. To estimate and map, at a regional scale (e.g., Northern Quebec) the vulnerability of the tundra to climate shifts.

KNOWLEDGE MOBILIZATION

- 52 presentations at scientific conferences
- 24 interviews with online, print and broadcast media
- Nine northern research partners mentored
- Eight meetings with Wildlife management decision-makers (Nunavut)
- Four popular science articles written based on our research
- Three meetings with Biodiversity conservation decision-makers (Quebec)
- Three northern communities (Cape Dorset, Coral Harbour, Resolute Bay) visited for results sharing workshops
- Two education Information Sharing workshops held in community schools (Arctic College in Iqaluit, High School in Resolute Bay)
- Creation of the northern biodiversity web site to share wildlife observations among community members (Inuktitut version at http://pondinlet.northernbiodiversity.ca/iu)
- Collaborations to the documentary movie "Le Harfang des neiges" focusing on our work in Igloolik and Bylot (produced by Bellefeuille Production for TV5)
- Participation to the workshop Atelier autochtone interculturel : Savoirs scientifiques et locaux en recherche nordique, Université de Montréal
- Participation in the organization of three workshops presented during the Student Day of the 2016 ArcticNet meeting
- Posting of multiple entries on the Facebook page of the Bylot Island research camp (https://www.facebook.com/goosecampbylot/)
- Organization of an exhibit on northern biodiversity at the Regional museum of Rimouski, Quebec, Canada during the 2016 summer-fall seasons
- Strong participation (three invited talks and three posters) at the Canadian Museum of Nature event on Canada's Arctic Biodiversity: The Next 150 Years
- Active participation during the Arctic Circle Forum, Québec city, December 2016
- Co-animation, with Guy Caron, Member of Parliament, of a public consultation on climate change adaptation and mitigation
- Preparation of the 5th International conference in Arctic Fox Biology (2017, Rimouski)

INTRODUCTION

The scientific context of our project has not changed since last year. In short (details and references in our 2015-2016 report), climate shifts impact the services that humans derive from their environment, particularly in the Arctic where snow and ice physically structure ecosystems (Berteaux et al. 2017). Wildlife monitoring is thus critical to track ongoing ecological changes, and understanding of the relationships between species and climate is required to interpret and predict variation in wildlife populations.

Our past work has shown that climate shifts may transform tundra food webs through multiple pathways, such as through changes in the species composition and abundance of predators. While wildlife management usually focuses on a few species valuable to humans, many stakeholders need information about components and drivers of change of ecosystems that involve higher levels of organization. Thus, a key recommendation of the Report for Policy Makers of the Arctic Biodiversity Assessment (Meltofte et al. 2013) was "the necessity to take an ecosystem-based approach to management, as a framework for cooperation, planning and development". One main difference between the species and ecosystem levels of ecological investigation is that the ecosystem level emphasizes interactions between species, including humans.

Increasing and updating the observational basis needed to address the ecosystem-level questions raised by climate change and modernization in the Arctic is a major objective of ArcticNet. Our project has worked in 2016-2017 towards improved wildlife monitoring and ecological understanding in the Eastern Canadian Arctic, and has made substantial progress in developing new approaches and new knowledge regarding ecosystem-level impacts of climate change.

ACTIVITIES

Time frame and study area: Field work was carried out from May to September 2016 at East Bay (Southampton Island), Rankin Inlet, Mary River (Milne Inlet to Steensby Inlet), Igloolik, Baker Lake, Digges Island, Coats Island, and Bylot Island. Boat-based bird, benthic invertebrates, and polar bear research was carried out in summer 2016 at East Bay and along the south coast of Hudson Strait in partnership with the community of Cape Dorset.

Research: Intensive field work was done and detailed analyses of collected data (capture and marking of wildlife, nest abundance, nest survival, digital pictures, acoustic recordings, locations of animals and movement behavior, avian and mammal distance sampling, avian disease sampling) and samples (tissues from wolf, wolverine and bear carcasses, lemming winter nests, predators and prey faeces, predator skulls, bird of prey pellets, plant above-ground biomass, insects and spiders, wildlife blood, hairs/feathers) were performed. Particular effort was made to synthesize existing data and integrate them into circumpolar research efforts. This resulted in the following investigations:

Weather

- Retrieval of annual weather data from four automated weather stations on Bylot Island, two at Rankin Inlet, two at East Bay (Southampton Island), and one at Coats Island. One semi-automated station was used in Igloolik.
- Retrieval of annual snow condition data from two automated environmental monitoring stations on Bylot Island and from one semi-automated station in Igloolik.

Plants

- Monitoring of plant primary production and goose grazing impact in wetland habitats at Bylot Island (24 exclosures).
- Monitoring of lemming grazing impact at Bylot Island (16 exclosures).
- Monitoring of arthropods and goose browsing in eight plots in Igloolik.
- Long-term monitoring of an ITEX site in Igloolik.

Arthropods

- Monitoring of insect and spider emergence and diversity using pitfall traps on Bylot Island (≥1000 samples collected over the summer) and modified malaise traps and pitfalls at Igloolik Island (≥500 samples collected over the summer).

- Collection and monitoring of hemiparasites wasps in Igloolik and on Bylot Island as part of an international effort to map biodiversity changes.

Birds (raptors)

- Monitoring of ca. 350 peregrine falcon, gyrfalcon and rough-legged hawk nest sites at Rankin Inlet, Igloolik, Baker Lake and Mary River.
- Monitoring of chick growth rate from 30 raptor nests at Rankin Inlet.
- Observation of peregrine behavior, breeding phenology, causes of mortality and identification of marked birds using infrared-triggered cameras and direct observation.
- Banding of 120 peregrines and rough-legged hawks at Rankin Inlet and Mary River.
- Monitoring of the reproductive activity of 30 nests of rough-legged hawks (among 96 known potential nesting sites visited), four nests of snowy owls, five nests of peregrine falcons (among 10 known potential nesting sites visited), and one nest of gyrfalcon at Bylot Island.
- Marking of seven adult rough-legged hawks with GSM transmitters at Bylot Island.
- Sampling of snowy owl and hawk pellets (>100) at Igloolik Island and Bylot Island.
- Acoustic recording of biodiversity at snowy owl and hawk territories on Bylot.

Birds (shorebirds and passerines)

- Monitoring of ca. 100 shorebird nests and 65 passerine nests at Bylot Island.
- Marking of ca. 60 shorebirds and ca. 200 passerines at Bylot Island.
- Deployment of 22 geolocators on shorebirds (common-ringed plovers) and recovery of previously deployed geolocators from three American golden-plovers and seven common-ringed plovers on Bylot Island.
- Monitoring of the growth rate of 75 known-aged snow bunting chicks from 23 nests on Southampton Island.
- Monitoring of 250 shorebird and 60 passerine nests at Igloolik Island.
- Marking of ca. 60 shorebirds, with 15 equipped with geolocators (GLS) at Igloolik Island.
- Monitoring of 15 snow bunting nest survival at Igloolik Island.
- Monitoring of body condition of 30 red phalaropes at Igloolik Island.
- Monitoring of mercury levels in 50 shorebirds at Igloolik Island.
- Acoustic recordings of shorebird and passerine phenology at Igloolik and Bylot Island.

Birds (geese and seabirds)

- Monitoring of reproductive activity of 337 nests of snow geese at Bylot Island.
- Monitoring of reproductive activity of 48 nests of long-tailed jaegers, five nests of parasitic jaegers, and 43 nests of glaucous gulls at Bylot Island.
- Banding of 18 long-tailed jaegers, deployment of 20 geolocators on jaegers and recovery of 16 previously deployed geolocators at Bylot Island.
- Banding and re-sighting of 200 adult eider ducks on Southampton Island to estimate annual survival of birds in relation to disease, harvest, and weather conditions.
- Capture and banding of 4357 snow geese with leg bands, including 678 adult females with neck-collars, at Bylot Island to monitor survival and recruitment.
- Collection of blood samples and nail clippings from 300 eider ducks on Southampton Island to assess links between hormones, body condition, and overwintering location.

- GPS tracking of 50 common eiders paired with hormone implants and egg collections (30 nests) to examine the influence of physiology on foraging behavior and reproductive success.
- Ongoing satellite tracking of common and king eiders to determine marine habitat use in the Canadian Arctic and West Greenland.
- Surveying of common eider breeding colonies in Hudson Strait to evaluate the severity and geographic scope of avian cholera and polar bear nest predation.
- GPS tracking of 134 thick-billed murres from Digges Island and 57 thick billed murres from Cape Graham Moore nesting colonies to identify key foraging habitat areas during the breeding season.
- Monitoring of the reproductive activity of six nests of long-tailed jaegers and two parasitic jaegers at Igloolik Island.
- Banding of five long-tailed jaegers and deployment of five geolocators on jaegers at Igloolik Island.
- Collection of ca. 500 faeces from all avian herbivores species (e.g. ptarmigans, geese) to measure their diet at Bylot and Igloolik Islands.
- Monitoring temporal and spatial variation in nest predation risk using artificial nests (Bylot Island and Igloolik Island).

Mammals

- Monitoring of 110 fox dens and of 27 arctic fox yearly movements at Bylot Island using Argos satellite transmitters.
- Monitoring of short- and long-range movements of arctic foxes breeding on Bylot.
- Monitoring of lemming abundance and demography at Bylot Island (389 winter nests sampled; live-trapping of 181 brown lemmings and 63 collared lemmings during 4300 trapping days; snap-trapping of 24 brown lemmings and 18 collared lemmings during 2300 trapping-days; counts of burrows and feces at 192 pairs of 60 m-transects).
- Monitoring of lemming abundance at Rankin Inlet (500 snap trapping days).
- Monitoring of 21 ermine dens and 50 shelter boxes at Bylot Island.
- Observation of fox behaviour on Bylot using 50 infrared-triggered cameras.
- Determination of reproductive effort of >100 wolverines and wolves by analysing reproductive tracks of animals harvested in Nunavut during 2012-2014.
- Monitoring of five fox dens in Igloolik, with sampling of faeces and diet remains.
- Monitoring of lemming abundance and demography at Igloolik Island (winter nests sampled; live-trapping and snap-trapping; counts of burrows and feces).
- Collection of ca. 100 faeces from all mammalian herbivores species (e.g. hares, caribou, lemmings) to measure their diet at Bylot and Igloolik Islands.
- Biopsy darting of three polar bears along the south coast of Baffin in collaboration with Cape Dorset HTO to evaluate through genetics how many bears use the area in July.
- Monitoring relative abundance of herbivores using 10-20 faeces transects (Bylot Island, Igloolik Island).

Syntheses

- Synthesis across several circumpolar study sites of climatic and ecological factors structuring tundra ecosystems.
- Further consolidation of the Circumpolar Arctic Fox Research Network to facilitate data synthesis on this species, recognized as priority focal ecosystem component by the Circumpolar Biodiversity Monitoring Program.

- Synthesis across several circumpolar study sites through involvement in the Circumpolar Seabird Working Group of the Arctic Council.
- Coordination and implementation of the circumpolar project "indirect trophic interactions" to understand and predict cascading effects in arctic terrestrial vertebrate communities.
- Development of ArcticWEB, a network to help determine concerted research efforts in terrestrial arctic ecology.
- Preparation of an important synthesis on the effects of changing permafrost and snow conditions on tundra wildlife, with reference to the critical places and times where such effects should be investigated.

RESULTS

We present examples illustrating results obtained for each of our four objectives.

Stakeholder perspectives on triage in wildlife monitoring (Objective 1)

Monitoring activities provide a core contribution to wildlife conservation in the Arctic as they allow changes in population status to be detected early, providing opportunities to mitigate pressures driving declines. Monitoring triage involves decisions about how and where to prioritise monitoring activities. For example, monitoring triage examines whether to divert resources away from species where there is high likelihood of extinction in the near-future in favour of species where monitoring activities may produce greater conservation benefits. As a place facing serious logistic and financial challenges for field data acquisition, the Arctic provides a good context in which to examine attitudes toward triage in monitoring.

We interviewed 23 individuals from six countries who were stakeholders in arctic wildlife monitoring to elicit their perspectives on triage in wildlife monitoring. Interviewees were selected from attendees at Arctic Council working group, international conferences, and via snowball or referral sampling among interviewed participants

The majority (56%) of participants opposed triage, 26% were in support and 17% were undecided. Representatives of Indigenous organizations were more opposed to triage than scientists, and those involved in decision-making showed greatest support for triage amongst the scientist participants (Figure 1). Some common responses to the concept of triage were that: 1) the species-focussed approach associated with triage did not match their more systems-based view, 2) important information is generated through monitoring threatened species, which advances understanding of drivers of change, 3) there is an obligation to monitor and conserve threatened species, and 4) monitoring has to address local people's needs, which may be overlooked under triage.

Large scale movements of migratory birds (Objective 1)

Rough-legged Hawks are important avian predators in the Canadian Arctic. They are small mammal specialists, thus breeding activity is generally associated with local abundance of ground squirrels, voles or lemmings (Hanski et al. 1991). They prey on birds when small mammals are scarce, particularly juvenile passerines and shorebirds, and resort to consuming carrion opportunistically. Detailed study of their breeding ecology is lacking. In 2016 we captured breeding adults and deployed 13 Solar GPS data-loggers (23 g) attached in the backpack position (Figure 2). Results show that outward migration began in late September 2016. Departure dates ranged from 29 September to 4 October, migration duration was approximately 68 days, mean travel distance averaged 3,815 km, and travel rate averaged 65 km/day (Figure 3).

Variation in marine habitat use of Thick-billed Murres (Objective 1)

We tracked Thick-billed Murres nesting in Digges Sound from 2012-2015 to identify key marine habitats. The Murres utilized a larger marine habitat area when they were incubating eggs (Figure 4, top panels) than when they were feeding chicks (bottom panels). This is likely because the energetic and time demands while incubating are much different than when an adult must also collect food to provision a chick. Marine habitat use differed across years (Figure 4, compare left, center and right panels). We now need to determine if sea-ice conditions influence duration and distance of foraging trips.

Partitioning prediction uncertainty in climate-dependent population models (Objective 2)

We quantified components of uncertainty surrounding the future abundance of the greater snow goose, using a process-based demographic model coupled with climate warming scenarios. We decomposed the uncertainty in predicted changes in animal population size into its components due to uncertainty in climate scenarios, uncertainty in the demographic model, climatic stochasticity, environmental stochasticity unexplained by climate-demographic traits relationships, and sampling variance in demographic parameter estimates. Our model predicts a slow population increase but with a large prediction uncertainty (Figure 5). The contribution of sampling variance to prediction uncertainty rapidly overcomes that of process variance and dominates (Figure 6). Interestingly, uncertainty in the climate scenarios contributed <3% of the total prediction variance over a 40-year period, much less than environmental stochasticity.

Links between climate warming and sea ice use by caribou (Objective 2)

Global warming threatens to reduce population connectivity for terrestrial wildlife through significant and rapid changes to sea ice. To model such a threat, we produced a Peary caribou and sea ice model (Jenkins et al. 2016). We found a strong correlation between genetic fingerprints and geographic distances for both continental and Peary caribou, even after accounting for the possible effect of sea surface conditions (Figure 7).

We also examined whether sea-ice contractions in the last decades modulated population connectivity and explored the possible impact of future climate change on long-term connectivity among island caribou. Using a time series of remote sensing sea-ice data, we showed that landscape resistance in the Canadian Arctic Archipelago has increased by approximately 15% since 1979 and may further increase by 20–77% by 2086 under a high-emission scenario (RCP8.5; Figure 8).

Effects of winter weather conditions on common eider populations (Objective 2)

We analysed long-term capture-mark-recapture data collected in two arctic (northern Canada and Svalbard) and one subarctic (northern Norway) common eider populations (Figure 9). Survival of female eiders varied over the study period and winter weather conditions affected survival in all three populations. However, different mechanisms seemed to be involved. Survival in the two arctic populations was impacted directly by changes in the North Atlantic Oscillation (NAO), whereas the subarctic resident population was affected by the NAO with time lags of two to three years. Moreover, the survival response to the winter NAO differed among populations in Canadian eiders, where individuals migrate to distinct wintering areas (Greenland or Atlantic Canada).

Exposure of the tundra of Ungava Peninsula to climate change (Objective 3)

The northern tip of the Ungava Peninsula is located north of the tree line. This is a very interesting area to study the "borealisation" of the Arctic tundra caused by climate change, because 1) local temperatures have strongly increased in the last decade, with associated

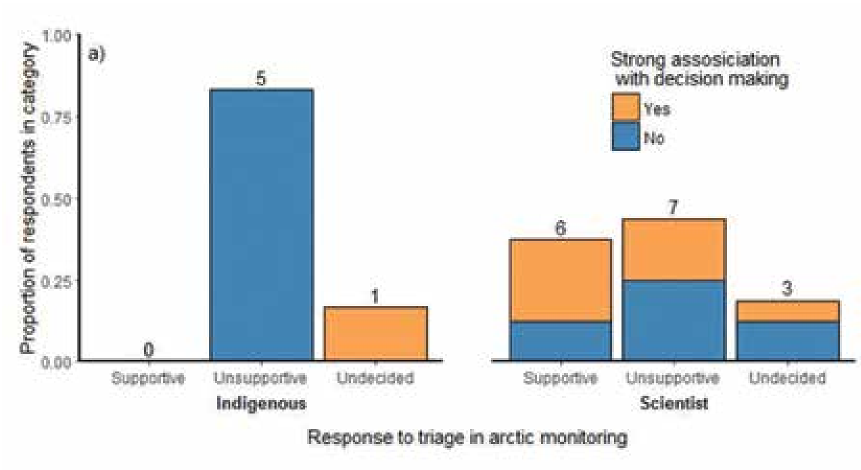

Figure 1. Summary of stakeholder responses to triage in arctic monitoring shows differences between representatives of Indigenous groups and scientists. Numbers of participants responding in a given way are indicated above bars. Modified from Wheeler et al. (2016). © 2016 Wheeler, Berteaux, Furgal, Parlee, Yoccoz and Grémillet.

loss of permafrost, 2) increased shrub growth is well documented (McManus et al. 2012), 3) no geographical barrier prevents boreal species from colonizing the area, 4) Inuit already see new species reaching the region (black bear, snowshoe hare, etc.), and 5) decision makers in the Quebec government currently need to take into account climate change into northern biodiversity conservation plans (Berteaux 2013).

We have worked with Ouranos to produce a set of data and maps that illustrate the exposure of the tundra of the Ungava Peninsula to climate change. For example, we have mapped the difference in annual growing degree days (> 5°C; GDD) between 1981-2010 and 2071-2100 (Figure 10). Future climatic scenarios based on RCP 8.5 predict an average increase of 7.0°C in mean annual temperature for the Ungava Peninsula. This results in an important increase in GDD over the area, especially in the southwestern part where as much as 950 GDD could be added annually (Figure 10).

Vulnerability of the tundra of Ungava Peninsula to climate change (Objective 4)

We used species distribution models (Berteaux et al. 2010) to project recent (1981-2010) and potential future (2071-2100) potential distribution of >200 bird and mammal species in northern Quebec. Recent distributions were taken from BirdLife and NatureServe. This allowed us to calculate a potential species turnover between the two periods, assuming that species are able to track perfectly and without delay their climatic niche. The potential turnover in bird and mammal species between 1981-2010 and 2071-2100 is high, ranging from 74 to 92% (Figure 11). No clear spatial pattern was found in this potential turnover, although lower values were found in the northern and southernmost regions.

Our assumption that species can track perfectly their climatic niche is known to be false, so that Figure 11 only provides a useful indication of the pressure that climate change imposes on biodiversity, not the detailed projection that we would need. We know that species interactions will have a major influence on the reorganization of biodiversity (for example, lynx will not colonize the northern tip of Quebec unless snowshoe hare first does so). We have thus collected large amounts of literature data and expert knowledge to build a detailed matrix of predator-prey interactions in Northern Quebec (Figure 12). This matrix will be used in 2017 to do more refined analyses of ecosystem vulnerability.

Figure 2. Mat Tétreault (left) and Jeff Kidd attach a transmitter to an adult female Rough-legged Hawk near Rankin Inlet. The bird's eyes are covered to limit stress (yellow arrow) and the GPS logger is of small size (23 g) to limit discomfort. Source: Alastair Franke.

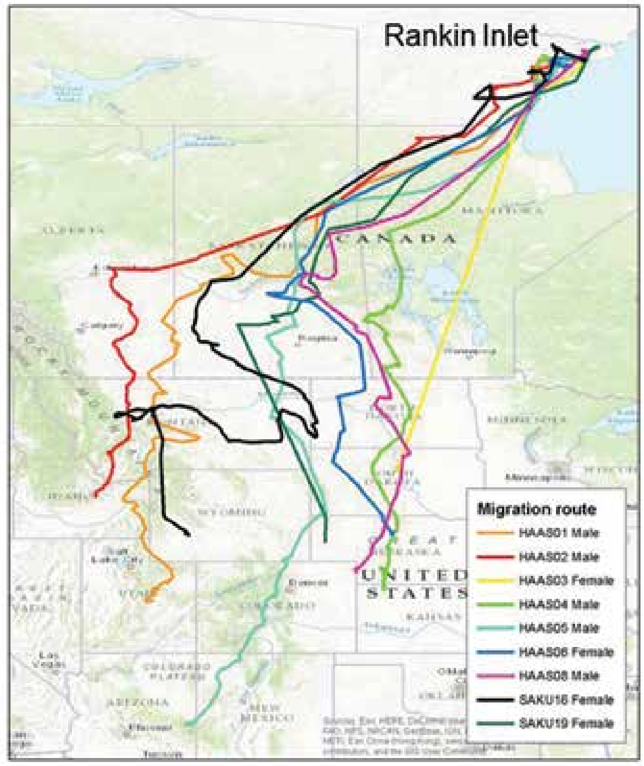

Figure 3. Outward migration tracks as of November 30, 2016 of eight Rough-legged Hawks breeding near Rankin Inlet. Source: Alexandre Paiement.

DISCUSSION

Stakeholder perspectives on triage in wildlife monitoring (Objective 1)

The complexity of decision making about how to design monitoring programmes that maximise benefits to biodiversity and people makes prioritisation difficult. Using scenarios to identify desirable trajectories of Arctic stewardship may be a particularly effective means of identifying monitoring needs. Further understanding is also needed of the connections between monitoring and positive impacts for society and biodiversity.

Large scale movements of migratory birds (Objective 1)

Our data suggest that phenology of Rough-legged Hawks breeding in Nunavut lags phenology of Rough-legged hawks breeding in the western Arctic (e.g. Alaska). Kidd et al. (2015) indicated that fall departure dates in the western Arctic ranged from 8 September to 29 September. Mean travel rate for birds from the western Arctic was 78 km/day. We now need to compare more thoroughly data from various populations and address the consequences of these geographic disparities.

Variation in marine habitat use of Thick-billed Murres (Objective 1)

Increases in resource development activities will increase shipping traffic in the Canadian eastern Arctic, but we lack information to properly assess ecological impacts of year-round shipping lanes on marine wildlife. We have tracked Murres from 2012-2015 to properly identify their key marine habitat areas and understand how habitat use changes annually and seasonally. These results will allow us to model changes in habitat use as function of

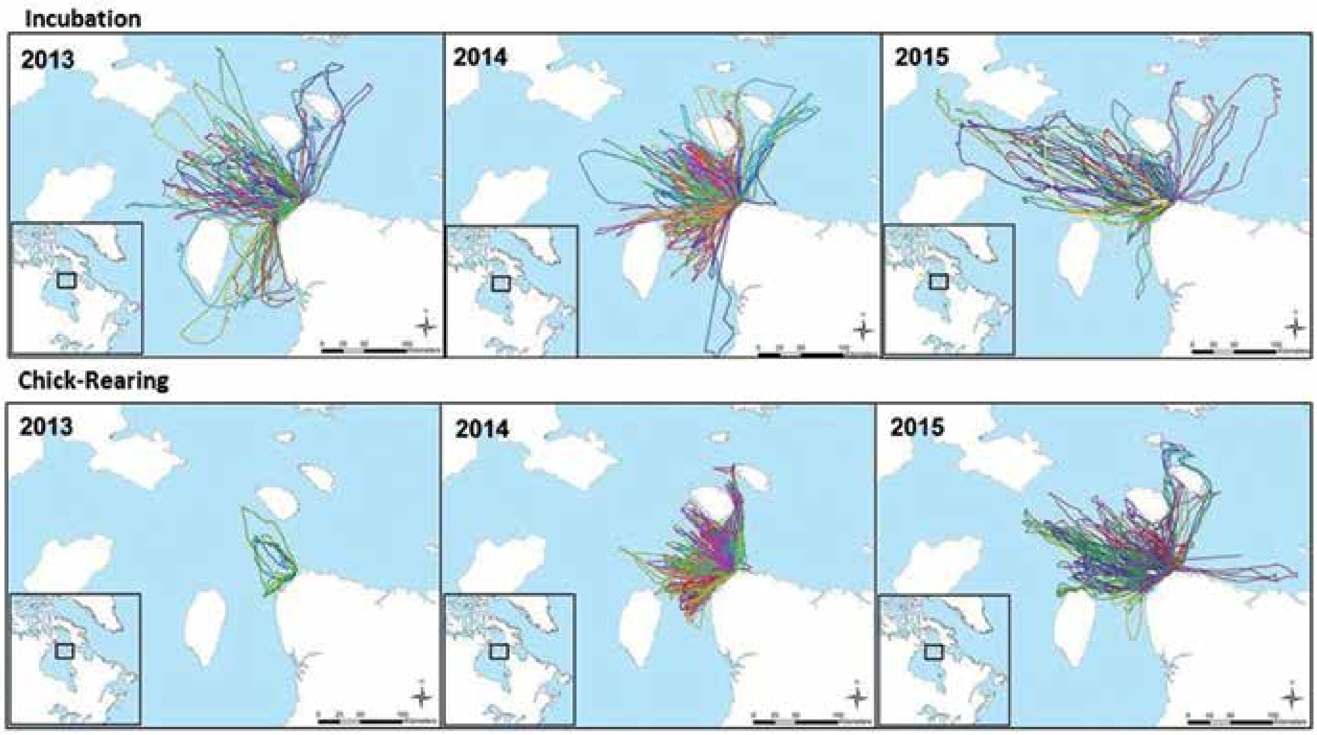

Figure 4. GPS tracks of Thick-billed Murres during incubation and chick rearing in Digges Sound 2013-2015 (only three individuals were tracked during chick rearing in 2013).

season and ice conditions, which will have important consequences for mitigating potential interactions with industrial shipping.

Partitioning prediction uncertainty in climate-dependent population models (Objective 2)

Predicted changes in animal population size based on climate-dependant demographic models entail a large part of uncertainty, which is often not communicated by researchers. We measured the contribution of the different sources of uncertainty in demographic projections, one of the main tools for scientists interested in the ecological consequences of climate change. We show that uncertainty linked to climate scenarios can be overwhelmed by environmental stochasticity. Efforts should thus be primarily devoted to reduce measurement error (mostly through additional field work) if one wishes to improve confidence in predicted change in animal populations exposed to climate warming based on demographic models.

Links between climate warming and sea ice use by caribou (Objective 2)

Our caribou model of sea ice use signalled that up to now, sea ice has been an effective corridor for Peary caribou to travel between the numerous islands of the Canadian Arctic archipelago, used as breeding grounds and foraging areas. Under the persistent increase in greenhouse gas concentrations, inter-island connectivity can decline at a fast pace, isolating populations of a key tundra herbivore (COSEWIC 2004) with potentially significant consequences for population viability and ecosystem dynamics.

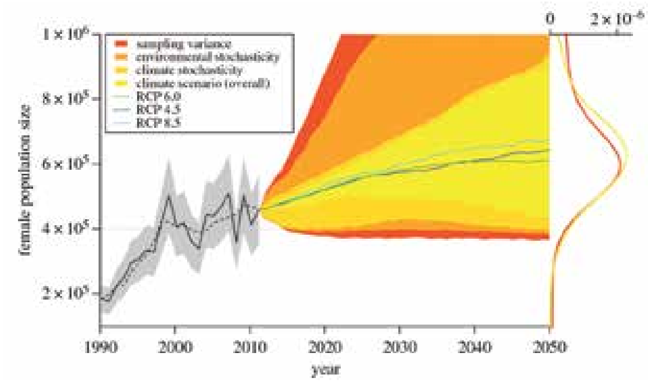

Figure 5. Observed (black line) and predicted (dashed line) population trajectory from 1990-2011 (gray area: 95% confidence interval) and mean projected trajectories from 2012-2050 (colored lines) under three scenarios of future anthropogenic greenhouse gas emissions. Coloured area: 90% projection intervals decomposed according to various sources of uncertainties (see text). The probability density curves in the right panel represent the distributions of projected population sizes in 2050 when considering only the uncertainty in the climate scenario (yellow) or all sources of uncertainty (red). From Gauthier et al. 2016. © 2016 Gauthier, Péron, Lebreton, Grenier, van Oudenhove. Published by the Royal Society. All rights reserved.

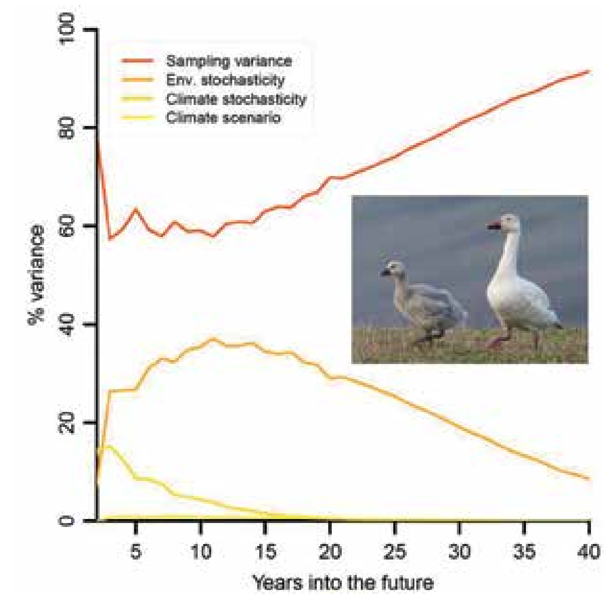

Figure 6. Change over time in the relative contribution of the various sources of uncertainty to the empirical prediction variance. Modified from Gauthier et al. 2016. © 2016 Gauthier, Péron, Lebreton, Grenier, van Oudenhove. Published by the Royal Society. All rights reserved.

Effects of winter weather conditions on common eider populations (Objective 2)

Our findings illustrate how individuals and populations of the same wildlife species can vary in their responses to climate variation. We suspect that variation in survival response of birds to winter conditions is partly explained by differences in migration tactics. Detecting and accounting for inter- and intra-population heterogeneity will improve our predictions concerning the response of wildlife to global changes (Kendall et al. 2011). This is one of the key goals of our ArcticNet project.

Exposure and vulnerability of the Ungava tundra to climate change (Objectives 3-4)

Preliminary modeling of the wildlife community (here, birds and mammals) suggests that the important climate shifts underway in northern Quebec will lead to a substantial reorganisation of the tundra ecosystem. We now need to considerably refine these preliminary results, by adding to our models predator-prey relationships and potentially projections about vertical structure of plant communities. Yet it is already obvious that the modeling approaches used in Northern Quebec have potential to be scaled up at a much larger scale, and thus be informative for other parts of the Canadian Arctic.

CONCLUSION

We have maintained, and in some cases intensified, our long-term monitoring of wildlife populations (Objectives 1 and 2) to detect any ecological shift that did not occur before or was not apparent in shorter time series. This important monitoring effort provides the needed observation stations and results for the ArcticNet Integrated Regional Impact Assessments, to which we have contributed (Franke et al. in press) through IRIS 2. This continues to strengthen the fundamental objective of the IRIS framework.

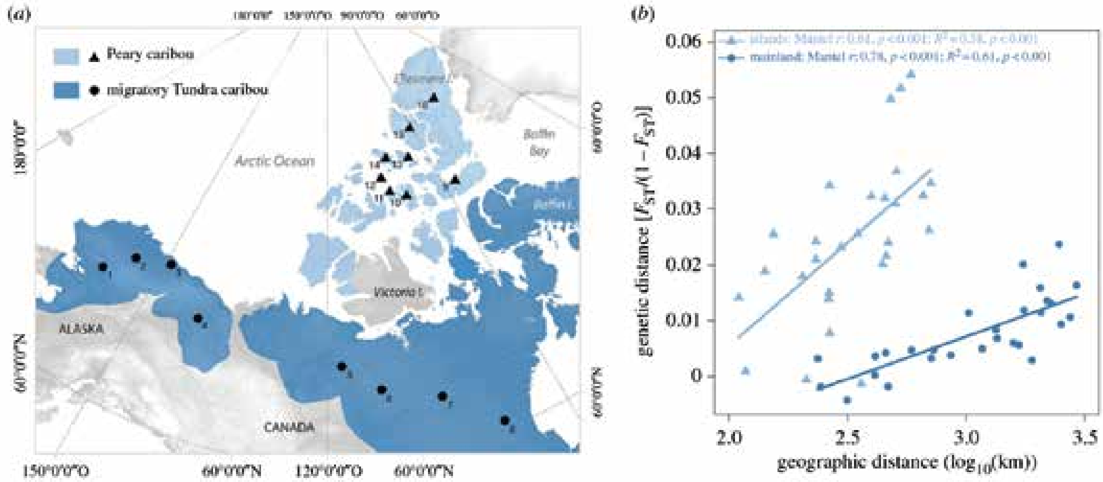

Figure 7. (a) Map of the study area. Shaded areas correspond to the range of continental-migratory tundra caribou and island-dwelling Peary caribou. Numbers correspond to the 16 herds sampled for the study (for example, Herd 16 is the herd from Ellesmere Island); b) Correlation between genetic and geographical distances among caribou populations. Dark blue circles correspond to continental herds and light blue triangles to island herds. From Jenkins et al. (2016). © 2016 Jenkins, Lecomte, Schaefer, Olsen, Swingedouw, Côté, Pellissier, Yannic. Published by the Royal Society. All rights reserved.

We have also integrated data from our field studies via predictive models of ecosystem exposure and vulnerability (Objectives 3 and 4). Such exercise, combining our field knowledge with literature data, governmental information, and expert knowledge, will be relevant to multiple stakeholders interested in northern wildlife and biodiversity.

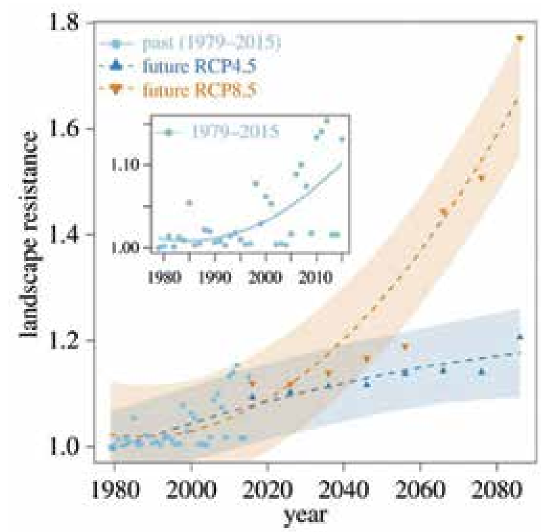

Figure 8. Connectivity changes over time in the Canadian Arctic for 1979–2015 and for the next 70 years (RCP4.5 and RCP8.5 scenarios). Inset: connectivity trend over 1979–2015. Trend lines and 95% CI of the predicted connectivity changes are represented with solid and shaded areas, respectively. Modified from Jenkins et al. (2016). © 2016 Jenkins, Lecomte, Schaefer, Olsen, Swingedouw, Côté, Pellissier, Yannic. Published by the Royal Society. All rights reserved.

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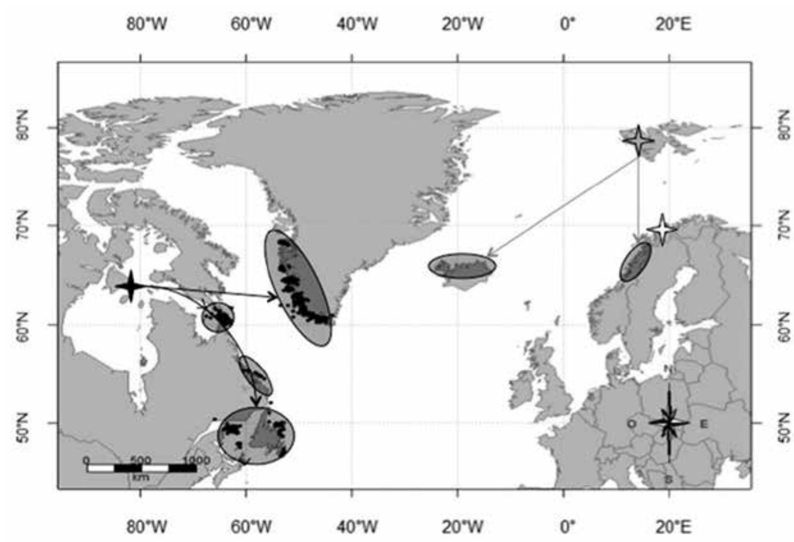

Figure 9. Winter distribution (ellipses) of female Common eiders breeding in Canada (black star), Svalbard (grey star) and northern Norway (white star). Black dots show winter locations of 26 females tracked with satellites from East Bay (Canada).

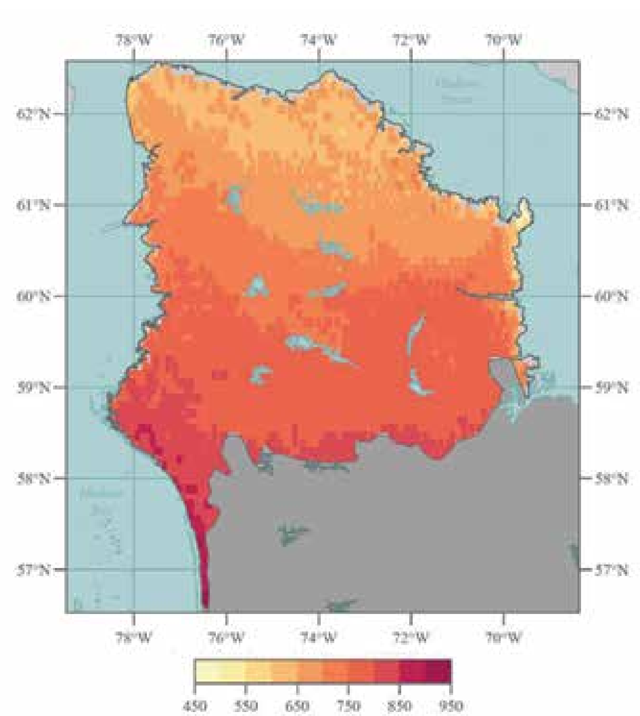

Figure 10. Predicted changes in annual growing degree days (>5°C) in the tundra of the Ungava Peninsula (northern Quebec) between 1981-2010 and 2071-2100 (RCP8.5).

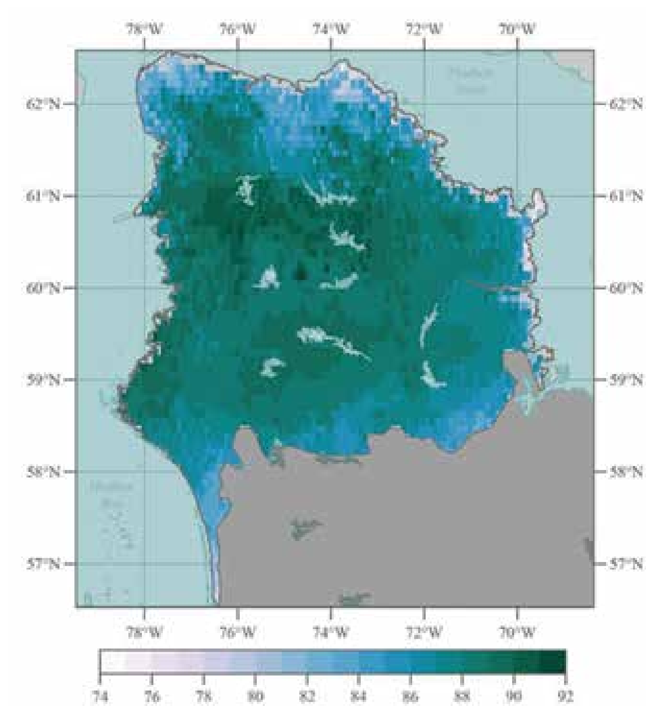

Figure 11. Potential turnover of species composition (mammals and birds) in the tundra of the Ungava Peninsula (northern Quebec) between 1981-2010 and 2071-2100, if all species tracked their climatic niche perfectly and without delay (RCP8.5 scenario).

			Predators								
			Species 1 Falco peregrinus	Species 2 Aquila chrysaetos	Species 3 Bubo scandiacus	Species 4 Corvus corax	Species 5 Dicrostonyx hudsonius	Species 6 Lepus americanus	Species 7 Lepus arcticus	Species 64 Vulpes vulpes	Species 65 Vulpes lagopus
Preys	Species 1	Falco peregrinus	0	0	0	0	0	0	0	0	0
	Species 2	Aquila chrysaetos	0	0	0	0	0	0	0	0	0
	Species 3	Bubo scandiacus	0	0	0	0	0	0	0	0	0
	Species 4	Corvus corax	0	1	0	0	0	0	0	0	0
	Species 5	Dicrostonyx hudsonius	1	1	1	1	0	0	0	1	1
	Species 6	Lepus americanus	0	1	0	0	0	0	0	0	0
	Species 7	Lepus arcticus	0	1	0	0	0	0	0	1	1
	Species 64	Vulpes vulpes	0	0	0	0	0	0	0	0	0
	Species 65	Vulpes lagopus	0	0	0	0	0	0	0	0	0

Figure 12. Partial view of the species interaction matrix for the Ungava Peninsula (northern Quebec). A predator-prey relationship is noted as "1" and a lack of predator-prey relationship is noted as "0". For example, Species 64 feeds from Species 7 whereas Species 65 does not feed from Species 2.

Koonoo, Randy Quaraq, Nik Clyde, Frankie Jean-Gagnon, Holly Hennin, Jenna Cragg, Ariane Batic, Oliver Love, Rolanda Steenweg, Kyle Elliot, Christine Anderson, Bob Hansen, Cody Dey, David McGeachy, Thomas Lazarus, Pierre Legagneux, Justin Roy, Will Black, Isabeau Pratte, Brian Malloure, Terry Kalluk, Jamie Enook, Randy Quaraq, Carey Elverum, Daniel Taukie, Meagan McCloskey, Sjoerd Duijns, Samuel Richard, Graham Sorensen, Bruen Black, Kerry Woo, Émile Brisson-Curado, Marie-Christine Frenette, William Lecomte, Josée-Anne Otis, Laurence Carter, Lindsay Gauvin, Laurent Montagano, Marie-Andrée Giroux, Kim Régimbald-Bélanger, Sam Piugattuk, Paul Allen Smith, Jennie Rausch, and other collaborators for their contribution to fieldwork. We thank Marie-Christine Cadieux, Elise Bolduc, and Nicolas Casajus for coordinating field activities on Bylot Island and managing our databases. We thank Marie-Andrée Giroux for co-leading the research activities at Igloolik and Cassandra Cameron, Josée-Anne Otis, and Jacinthe Gosselin for their logistical, permitting, and database support for the Igloolik project. We thank Mike Janssen and Jake Russell-Mercier for coordinating field activities at Southampton Island, Digges Island, Cape Graham Moore, and Cape Dorset. We also thank Josiah Nakoolak, Juipi Angootealuk, Clifford Natakok, Michael Shimout, Numa Ottokie, Charlie Qiatsuq, Adamie Qaumagiaq, Salamonie Aningmiuq, Luutaaq Qaumagiaq, Kovianaqtuliaq Ottokie, Tutuiya Qatsiya, Peter Ottokie, Kristiina Alariaq, Jamesie Alariaq and the staff at Huit Huit Tours, Adamie Samayualie, Adamie Nuna, Annie Suvega, Mike Qrunnuk, Samuel Piugattuk and Phillip Audlaluk, the Cape Dorset HTO, the Coral Harbour HTO, the Igloolik HTO, the Pond Inlet HTO, the Nunavut Inuit Wildlife Secretariat, and the Nunavut Wildlife Management Board for providing field assistance, local expertise, as well as community and logistical support. We are extremely grateful for the help and support received from personnel of the Department of Environment (Government of Nunavut), especially Drikus Gissing, Myles Lamont, Melanie Wilson, Guillaume Szor, Malik Awan, Lynda Orman, Mat Fredlund, Mike McPherson, Lisa-Marie Leclerc, and Moshie Kotierk. We are also very grateful to Susan Enuaraq, Mike Shouldice and Dorothy Tootoo from the Nunavut Arctic College, and to the people from Rankin Inlet, Coral Harbour, Cape Dorset, Ivujivik, Igloolik, Pond Inlet, Iqaluit and other communities as well as all Hunters and Trappers Organizations.

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POPULATION DYNAMICS AND PREDATOR-PREY RELATIONSHIPS IN MIGRATORY CARIBOU OF THE QUÉBEC-LABRADOR PENINSULA IN THE CONTEXT OF CLIMATE AND ANTHROPOGENIC CHANGES

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ABSTRACT

The proposed research builds upon a collaboration between academic scientists, government biologists, aboriginal organizations and private industry to better understand the ecology and conservation of migratory caribou, a key component of the ecology, economy and culture of Canada's north. We will examine how climate change, habitat modifications, industrial development, sport and subsistence hunting interact with changes in predation, population phases of caribou demography and environmental variability to affect the abundance and distribution of two herds of migratory caribou that are showing contrasted population trajectories. Our research team will combine state-of-the-art satellite technology, isotopic and nutritional analyses with innovative scientific hypotheses, statistical and modelling techniques, to provide government, Aboriginal organizations and industry with reliable information on minimizing the impacts of industrial activities and harvest on caribou population ecology. Our results will be essential to ensure the continued sustainable harvest of caribou by subsistence and sport hunters. Because our research will be based on a proven ability to monitor a very large sample of instrumented caribou and will test several innovative hypotheses, our team will continue to provide contributions of high scientific merit, advancing our understanding of northern ecology. We will also provide training for about seven graduate and six to eight undergraduate students, on subjects and within a northern ecosystem where advance knowledge in ecology and conservation are in very high demand.

KEY MESSAGES

- Access to hunting grounds, via roads and hunting camps, as well as visibility increase the vulnerability of migratory caribou during the hunting season.
- Preliminary results indicate that human disturbances can have single and cumulative effects on habitat selection behaviors of caribou.
- Ice availability influenced the movements of caribou. They selected ice and avoided water when migrating across or in the vicinity of large water bodies.
- Climate projections indicated that ice availability could decrease considerably before the end of the century, generating a ~28% increase in distance travelled by caribou during the early spring and fall migrations.
- Caribou herbivory can negatively impact the primary productivity of Arctic and subarctic terrestrial ecosystems, and these changes may subsequently affect caribou population dynamics and space use tactics.
- From November 2015 to November 2016, sport hunting decreased caribou survival by 13%, suggesting that hunting could have a large effect in the decline of the Rivière-George herd.
- New satellite collars equipped with video cameras yielded a much higher precision in the determination of birth date, survival rate, habitat choice and mortality of caribou calves.
- Most wolves exhibit long-distance migrations when caribou is abundant. Some black bears perform long-distance movements to access caribou calving grounds.
- A system to collect predator carcasses with Cree and Inuit trappers has been put in place and the first samples have been collected.
- A new experiment manipulating caribou browsing, snow accumulation and shading caused by increased shrub abundance was put in place in Deception Bay.

OBJECTIVES

Our multidisciplinary research program seeks to better understand the ecology and conservation of two herds of migratory caribou (*Rangifer tarandus*) in northern Québec and Labrador, the Rivière-George and the Rivière-aux-Feuilles herds. We aim:

1. to determine cumulative impacts of human disturbance on habitat selection and demography of migratory caribou (Ph.D. 1 – S. Plante);
2. to study the spatiotemporal use of migration corridors by caribou (Postdoc – M. Leblond);
3. to evaluate changes in space use of caribou using remote sensing (M.Sc. 1 – B. Campeau);
4. to identify the determinants of caribou survival (Ph.D. 2 – B. Vuillaume);
5. to study interactions between caribou and its predators (Ph.D. 3 – M. Bonin, Ph.D. 4 – R. Rogers);
6. to determine the indirect consequences of the intensification of the shrub layer on summer food resources of caribou (M.Sc. 2 – E. Lemay).

KNOWLEDGE MOBILIZATION

- Six scientific publications and 20 presentations at scientific conferences.
- Twelve radio interviews (including northern radios: CBC North-Quebec, Radio-Canada Terre-Neuve-Labrador, Radio-Canada Côte-Nord).
- Hosted two annual scientific meetings and an annual workshop to present the latest results to the different partners involved in the project (Universities, Governments, co-management-boards, Inuit organizations, private industries). Included decision-making and planning of future studies and field work.
- Four presentations and discussions of our study in Inuit communities (Salluit and Bay Deception, Nunavik) and with First Nation associations (Nunavik Hunting, Fishing and Trapping Association and Cree Trappers Association).
- One presentation in a high-school (Salluit, Nunavik).
- Three students participated in the "Atelier Autochtone Interculturel: Savoirs Scientifiques et Locaux en Recherche Nordique", April 2016.
- One student participated to the annual symposium of the Observatoire Hommes-Milieux international in Nunavik.
- One student participated at "Arctic Circle Forum" as a secretary, December 2016.
- One student participated to the "Arctic Frontiers Conference", Norway, as the winner of Emerging Leaders.

INTRODUCTION

The conservation and management of wildlife populations represent a central issue in northern areas of Canada that are increasingly affected by human development and threatened by climate change. Migratory caribou is a key element of the ecology of the north, where it is central for the culture and the economy of communities. Despite substantial research efforts, the factors explaining variations in the abundance of migratory caribou are not fully understood, making their management problematic (Festa-Bianchet et al. 2011). Most populations of caribou are decreasing and human disturbance and climate change are among the major proposed causes of the current circumpolar decline (Vors and Boyce 2009).

Two major migratory caribou herds inhabit northern Quebec and Labrador, the Rivière-George and Rivière-aux-Feuilles herds. These herds have recently undergone major demographic change with large temporal variations. Changes in the abundance and distribution of caribou may have serious impacts for indigenous people and the outfitting industry. The caribou are an important food source for the Inuit, Cree, Naskapi and Innu, who harvest more than 10,000 caribou per year. Northern Quebec and Labrador could be subject to radical increases in industrial activities with their high mineral potential and the development of the Plan Nord. These developments could have significant ecological and demographic consequences for migratory caribou and their predators. In addition, average temperatures in the Arctic have increased nearly twice as fast as the global average over the last 100 years, and significant additional warming at these latitudes is expected (IPCC 2014). Following the drastic reduction of populations, especially for the Rivière-George herd that decreased >98% of its abundance since the early 1990s, we do not know whether the populations are currently sustainable. Only sound knowledge on population dynamics would ensure the sustained use of the resource. Current knowledge does not allow to anticipate changes in abundance of caribou, or predicting an eventual return of abundant populations. To improve the management and conservation of migratory caribou, a long-term research program is essential. Indeed, the characteristics of caribou (e.g. long life expectancy, variable vital rates) necessarily involve high temporal variations. Furthermore, to understand the impact of density-dependent and independent factors (e.g. climatic factors), it is necessary to analyze a long-time series encompassing a wide range of conditions.

Our initiative seeks to advance our understanding of four major aspects of caribou conservation: 1) the cumulative effects of human activities (e.g. mining) on caribou space use and survival, 2) predator-caribou interactions, 3) population dynamics, to maintain subsistence and sport hunting and, 4) the impacts of climate change and demographic changes on caribou habitat. Migratory caribou are central to the economy and traditional life of Northern peoples and an understanding of their demography in a context of climate change and industrial development is essential for the IRIS of ArcticNet.

ACTIVITIES

Fieldwork activities

- January to September 2016 – We conducted captures of caribou, wolves and black bears on the Rivière-aux-Feuilles and Rivière-George ranges to increase the number of individuals wearing GPS collars (49 caribou, 16 wolves and 18 black bears).
- January to September 2016 – We conducted captures of caribou, wolves and black bears on the Rivière-aux-Feuilles and Rivière-George ranges to replace old collars.
- April 2016 – We deployed 14 camera collars on pregnant females from the Rivière-aux-Feuilles herd to estimate calf survival.
- June to September 2016 – We conducted fieldwork for the vegetation and climate experiments at Deception Bay.
- October 2016 – We performed the classification by age-sex classes of caribou from the Rivière-aux-Feuilles and Rivière-George herds and estimated recruitment.
- Autumn 2016 – We organized a recovery system of predator carcasses with Aboriginal people to collect tissue samples and digestive tracts.

Meetings, conferences and workshops

- May and November 2016 – We held scientific committee meetings of the caribou project to plan fieldwork activities for the summer and fall 2016, and winter 2017.
- Spring, Summer and Autumn 2015 – We presented our results on many occasions such as at the 16th North American Caribou Workshop (Thunder Bay, ON), the 41st Annual meeting of the Société Québécoise pour l'Étude Biologique du Comportement (Rimouski, QC), and the 12th Annual scientific meeting of Arcticnet (Winnipeg, MB).
- January 2016 to November 2016 – We presented the project on predator diets to the Cree Trapper Association and the Nunavik Hunting Fishing Trapping Association and developed a collaboration with northern communities to obtain predator samples.
- January 2017 – We presented our research program to the Environmental Symposium of Glencore – Mine Raglan in Salluit.

RESULTS

Objective 1. Cumulative impacts of human disturbance on habitat selection and demography of migratory caribou (Ph.D. 1 – S. Plante)

Our first objective was to identify landscape characteristics that could make caribou of the Rivière-aux-Feuilles herd more vulnerable to winter sport hunting. We evaluated the relative importance of habitat selection behaviors by caribou and sport hunters, as well as landscape characteristics (vegetation cover, elevation and proximity of human infrastructure) on the spatial distribution of caribou harvest. We used Resource Selection Functions (RSF) to describe habitat selection behaviors for 223 caribou between 1997 and 2015, and for 83 sport hunters between 2013 and 2015. We also characterized over 169,000 harvest sites between 1997 and 2014 according to landscape characteristics and the occurrence probability of caribou and hunters. We found that landscape characteristics better explain caribou vulnerability to sport hunting than caribou or hunters' behaviors. Caribou were more vulnerable in proximity to hunting infrastructures (roads and outfitter camps) than anywhere else in the landscape (Table 1). Caribou strongly avoided roads whereas hunters strongly selected them. Caribou selected for proximity to outfitter camps, possibly because camps were located in caribou traditional grounds. Caribou also avoided frozen lakes where visibility and detectability by hunters were higher. Finally, caribou were more vulnerable on less rugged areas (low elevation variation), possibly because these areas offer better access and visibility to hunters.

These results are part of a scientific publication:

- Plante, S., C. Dussault et S. D. Côté. 2016. Visibility and accessibility to hunting areas explain caribou vulnerability to sport hunting. Journal of Wildlife Management 81:238-247.

Our second objective was to evaluate the single and cumulative impacts of human disturbances on habitat selection for the Rivière-aux-Feuilles and Rivière-George herds during summer and winter. We first evaluated whether disturbances such as mines, mining exploration sites, power lines, villages, and other infrastructures outside villages (roads and buildings) were avoided by caribou (single effects). We also determined whether the densification of disturbances in the landscape could intensify avoidance responses by caribou (cumulative effects). We tested the effect of the distance to the nearest infrastructure of each type on the habitat selection of caribou using RSFs, and evaluated the relative importance of environmental variables (vegetation cover, vegetation productivity, and elevation), and human disturbances on habitat selection. In addition, we tested the effects of vegetation productivity on caribou tolerance to disturbances. Finally, we tested the effect of disturbance density at the nearest infrastructure from a caribou location on its habitat selection. The goal was to perform habitat selection analyses for two seasons (summer and winter), and at three spatial scales (within individual intensive-use areas, within individual home ranges, and within seasonal areas used by the entire population). Currently, only analyses for the within individual home range scale are completed and we present preliminary results. Both human disturbances and environmental characteristics influenced habitat selection in summer and winter for the two herds (Table 2). Individuals from both herds selected for areas with higher food resources availability (shrublands) in summer and avoided disturbed areas in winter. Habitat selection behaviors regarding human disturbances, however, were variable between seasons and between herds. For the Rivière-aux-Feuilles herd in summer, human disturbances had no effect on habitat selection, except for mines that were avoided. In winter, caribou of the Rivière-aux-Feuilles herd avoided exploration sites and selected for proximity to roads. Surprisingly, they selected for proximity to areas more densely disturbed in summer, probably a result of caribou using coastal areas to minimize insect harassment, where villages are mostly located (Table 3). We found, however, no evidence of disturbance density for this herd in winter.

In the RG herd, caribou selected for proximity to villages in summer and winter, but were not affected by other types of disturbances. In summer, caribou avoided areas more densely disturbed, but not in winter at the within individual home range scale (Table 4).

Objective 2. Spatiotemporal use of migration corridors by caribou (Postdoc – M. Leblond)

The objective was to evaluate the influence of climate change or more specifically, the influence of changes in the availability and phenology of ice forming on freshwater lakes and rivers, on the movements of migratory caribou in northern Quebec. Warmer temperatures could generate a mismatch between the migrations of caribou and the periods during which ice is present on lakes and rivers. If migratory caribou were unable to adjust the timing of their migrations, they could be forced to circumvent unfrozen water bodies more frequently and over broader areas, which could increase the distance, time, and energy they use to reach wintering areas and breeding grounds. We analyzed the movements of 96 migratory caribou from the Rivière-aux-Feuilles herd equipped with GPS telemetry collars between 2007 and 2014. We focused our analyses on the fine-scale movements of caribou in the vicinity of the largest water bodies present in their range. We divided caribou movements into three categories: ice crossings, water crossings, and detours (land) around the periphery of lakes and rivers (Figure 1).

We calculated movement metrics (i.e., movement rate and absolute turning angle) across three substrates (ice, water and land), and we determined that caribou movements were faster and more directional on ice and during detours compared to movements elsewhere in the study area (Figure 2). Conversely, caribou movements in water were slower and more convoluted. We performed a step selection function to determine whether migratory caribou selected for a specific substrate during their migrations and winter movements. We found that caribou selected ice ($\beta \pm$ error type: 0.48 ± 0.18, $p=0.01$) and avoided water when moving across or in the vicinity of large water bodies (-0.73 ± 0.36, $p=0.04$).

Finally, we projected the contemporary movements of caribou within a gradient of future ice phenology scenarios to determine the potential consequences of climate change on the movements of caribou during the next 25 – 50 years. Based on several climate models developed in northern Canada (e.g. Brown and Duguay 2011, Brammer et al. 2015), we simulated advances in thawing dates and delays in freezing dates of water bodies in our study area and we analyzed the proportion of ice crossings that would have been lost due to the absence of ice. Our climate projections indicated that ice availability could decrease considerably before the end of the century, generating a ~28% increase in distance travelled by caribou during the early spring and fall migrations.

This study is now completed and published:

- Leblond, M., M.-H. St-Laurent et S. D. Côté. 2016. Caribou, water and ice – Fine-scale movements of a migratory Arctic ungulate in the context of climate change. Movement Ecology 4:14.

Objective 3. Evaluation of changes in space use of caribou using remote sensing (M.Sc. 1 – B. Campeau)

Our goal was to examine the relationships between caribou herbivory and changes in the Rivière-George population size, range use, and habitat quality. We used the Normalized Difference Vegetation Index (NDVI) to examine trends in range productivity over the 1991-2011 period, representing the period of the greatest Rivière-George population decline. A modelling approach relating NDVI to climatic variables was used to control for the climate signal and isolate the influence of caribou herbivory on primary productivity. We were able to identify significant negative relationships between caribou density and primary productivity, after controlling for climatic variation, for both the global Rivière-George calving grounds and summer range (Figure 3). Positive temporal trends in primary productivity appeared to reflect the decline of the Rivière-George herd. However, the greening trend was largely the result of climate

Table 1. Selection coefficients (β) and 95% confidence intervals (CI) of the top-ranked resource selection models for harvest sites, caribou, and hunters on the Rivière-aux-Feuilles herd during the winter sport hunting season, northern Québec, Canada (harvest sites and caribou: 1997–2015, hunters: 2013–2015).

	Harvest sites			Caribou			Hunters		
		95% CI			95% CI			95% CI	
Landscape characteristic	β	Lower	Upper	β	Lower	Upper	β	Lower	Upper
Distance to road	4.12	3.44	4.79	-2.41	-3.32	-1.51	14.16	11.85	16.47
Distance to outfitter camp	4.38	3.70	4.79	1.38	0.10	2.65	2.53	1.47	3.59
Distance to building	0.86	-0.06	1.78	0.00	-0.63	0.63	-3.07	-4.61	-1.53
Distance to power line	-0.56	-1.22	0.11	-0.44	-1.21	0.34	N/A	N/A	N/A
Conifer forests with lichens (%)	0.12	0.03	0.21	0.11	0.06	0.17	0.01	-0.18	0.20
Open or disturbed areas without lichen (%)	-0.10	-0.21	-0.01	-0.04	-0.09	0.01	0.02	-0.09	0.12
Open areas with lichens (%)	-0.03	-0.14	0.09	0.04	0.00	0.08	0.11	-0.04	0.26
Lakes (%)	0.22	0.17	0.27	-0.10	-0.14	-0.06	0.00	-0.09	0.08
Mean elevation (m)	0.17	-0.01	0.35	-0.35	-0.49	-0.21	-1.38	-1.72	-1.04
Altitudinal range (m)	-0.25	-0.34	-0.15	0.00	-0.15	0.15	-0.04	-0.27	0.19
Conifer forest with lichen × Distance to road	0.22	0.08	0.36	0.36	0.15	0.57	0.45	0.03	0.87
Open or disturbed areas without lichen × Distance to road	-0.01	-0.15	0.14	-0.18	-0.35	-0.02	1.03	0.59	1.48
Open areas with lichens × Distance to road	-0.07	-0.15	0.14	-0.25	-0.44	-0.06	-1.21	-1.97	-0.45
Lakes × Distance to road	-0.42	-0.54	0.30	0.19	0.01	0.37	-0.36	-0.70	-0.02

warming, as exemplified by the correlations observed between primary productivity and climatic variables. We also identified a shift in calving grounds post-2000 from a large and productive area to a relatively small and unproductive area. The MSc is completed and the manuscript of the main chapter will be submitted to a scientific journal in February 2017.

Objective 4. Determinants of annual caribou survival by age and sex (PhD 2 – B. Vuillaume)

Our first objective is to identify the environmental determinants of adult survival. We will use Known-fate models to determine survival rate of males and females, considering multiple environmental determinants. These determinants will be treated as individual covariates: vegetation quality and availability (NDVI), temperature, precipitations, snow cover, winter characteristics (North Atlantic Oscillation (NAO) index that describes climate fluctuations at large spatial scale), predation and sport hunting. We will consider several temporal scales (months, seasons of activity, years, growth and decline periods of the herds) and difffent seasons of activity for each sex. Survival in migratory caribou has been highly variable through time and fluctuated with large-scale population trajectories. Female adult survival in large mammals is usually the main demographic parameter determining population growth rate (Gaillard et al. 2000). We performed preliminary analyses for the Rivière-aux-Feuilles herd for the periods November 2014-October 2015 (Figure 4), and November 2015-November 2016 (Table 4). Our initial results indicate that male survival was lower than female survival throughout the year (e.g. in 2014-2015, females = 0.83, SE = 0.08; males = 0.68, SE = 0.04). Models also suggested that survival rate changed with the season of activity. In addition to the monitoring of adult survival, we fitted camera collars on pregnant females to study calf survival. These collars recorded 10 seconds of video every 20 minutes during the first three months of the calf life (June 1st to September 1st). The 14 females survived and 13 calves were born. Among these 13 calves, at least eight were alive September 1st, which represents a minimum survival of 60% for our sample.

Table 2. Selection coefficients (β) and 95% confidence intervals (CI) of the top ranked resource selection models explaining single effects of human disturbances on summer (A) and winter (B) habitat selection for caribou of the Rivière-aux-Feuilles (RAF) and Rivière-George (RG) herds (Québec and Labrador, Canada).

A)

	RAF			RG		
		95% CI			95% CI	
Landscape attribute	β	Lower	Upper	β	Lower	Upper
Conifer forests	**0.09**	**0.03**	**0.16**	-0.02	-0.04	0.01
New or old disturbance (tundra fire)	**-0.14**	**-0.21**	**-0.08**	-0.03	-0.08	0.02
Shrubland	**0.05**	**0.03**	**0.07**	**0.08**	**0.06**	**0.09**
Low vegetation	**-0.03**	**-0.06**	**0.00**	**-0.04**	**-0.07**	**-0.02**
Lakes	**-0.05**	**-0.07**	**-0.02**	-0.02	-0.06	0.01
Elevation	0.11	-0.06	0.28	**-0.09**	**-0.16**	**-0.02**
NDVI (normalized difference vegetation index)	2.08	-4.37	8.54	**0.80**	**0.40**	**1.20**
Distance to nearest coast	**0.65**	**0.17**	**1.13**	**0.28**	**0.16**	**0.40**
Distance to nearest village	0.51	-0.10	1.12	**0.66**	**0.46**	**0.85**
Distance to nearest mine	**-0.57**	**-0.91**	**-0.23**	0.12	-0.10	0.34
Distance to nearest exploration site	-0.04	-0.31	0.23	-0.12	-0.29	0.05
Distance to village * NDVI	-0.32	-1.50	0.86	-	-	-
Distance to mine * NDVI	0.80	-0.21	1.82	-	-	-
Distance to exploration site * NDVI	-0.43	-1.41	0.56	-	-	-
Distance to village * Distance to coast	0.04	-0.07	0.16	-	-	-

B)

	RAF			RG		
		95% CI			95% CI	
Landscape attribute	β	Lower	Upper	β	Lower	Upper
Conifer forests with lichens	0.01	-0.01	0.03	0.01	-0.02	0.04
New or old disturbance (tundra fire)	**-0.03**	**-0.06**	**0.00**	**-0.05**	**-0.10**	**-0.01**
Open areas without lichens	**-0.12**	**-0.20**	**-0.05**	0.01	-0.07	0.08
Open areas with lichens	**0.14**	**0.09**	**0.18**	0.09	0.06	0.12
Lakes	**-0.04**	**-0.07**	**-0.02**	**-0.04**	**-0.08**	**0.00**
Elevation	-0.12	-0.29	0.05	**-0.38**	**-0.60**	**-0.16**
Distance to nearest coast	-0.68	-3.06	1.70	0.17	-0.66	0.99
Distance to nearest village	-0.10	-2.52	2.31	**1.22**	**0.18**	**2.26**
Distance to nearest mine	0.82	-0.16	1.80	-0.09	-0.46	0.28
Distance to nearest exploration site	**-0.54**	**-0.80**	**-0.28**	0.05	-0.10	0.20
Distance to nearest road (outside villages)	**0.28**	**0.09**	**0.48**	0.21	-0.08	0.50
Distance to nearest building (outside villages)	-0.08	-0.28	0.12	-0.10	-0.33	0.12
Distance to nearest power line	0.08	-0.11	0.28	0.13	-0.16	0.42
Distance to village * Distance to coast	-0.04	-0.52	0.43	0.13	-0.06	0.31

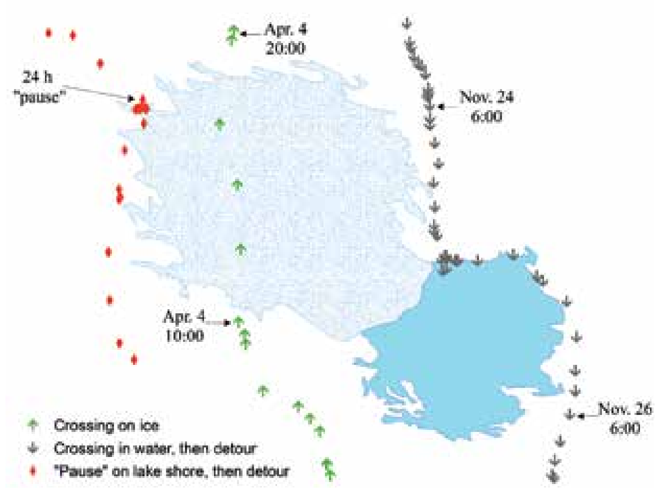

Figure 1. Examples of commonly observed movements of Rivière-aux-Feuilles caribou in the vicinity of one of the largest water bodies in their range, Clearwater Lake (Wiyâshâkimî). Prolonged "pauses" on water body shores before or after crossings and detours are illustrated using red diamonds. Fast and directional movements on ice are illustrated using green arrows. Unsuccessful attempts at crossing open water lakes are illustrated using grey arrows.

Objective 5. Interactions between caribou and its predators (Ph.D. 3 – R. Rogers, Ph.D. 4 – M. Bonin)

The primary predators in northern Quebec and Labrador are wolves (*Canis lupus*) and black bears (*Ursus americanus*) and while, locally, these predators may consume moose (*Alces americanus*) or muskox (*Ovibos moschatus*), caribou remains the primary ungulate prey for both these predators. Our first objective is to investigate and quantify spatial interactions and potential habitat overlap of wolves and black bears with caribou as well as quantify predation and the effects of predation on caribou distribution. Since 2011, both wolves and black bears associated with the Rivière-aux-Feuilles and Rivière-George herd ranges have been collared using GPS collars (Table 5). Using home ranges based on GPS relocations (Figures 5, 6) in association with GIS layers of habitat characteristics we will evaluate the habitat selection of both wolves and bears and whether this selection creates overlap with habitat selected by caribou. In addition, potential kill sites will be identified from GPS relocations using a clustering algorithm (Knopff et al., 2009) and associated to habitat types to produce a "predation risk" map and estimate the total potential predation by each predator in the system. Black bear GPS relocations will also be used to create clusters in an effort to predict multiple resting/foraging behaviours (i.e. bedding, plant-based foraging, or animal-based foraging; Cristescu et al. (2015)). Initial kill site investigations of 15 potential kill sites resulted in five confirmed caribou kill sites for wolves residing in the Rivière-aux-Feuilles herd winter range. Cluster

Table 3. Selection coefficients (β) and 95% confidence intervals (CI) of the top ranked resource selection models explaining cumulative effects of human disturbances on summer (A) and winter (B) habitat selection for caribou of the Rivière-aux-Feuilles (RAF) and Rivière-George (RG) herds (Québec and Labrador, Canada).

A)

	RAF			RG		
		95% CI			95% CI	
Landscape attribute	β	Lower	Upper	β	Lower	Upper
Conifer forests	0.10	0.04	0.17	-0.01	-0.03	0.02
New or old disturbance (tundra fire)	-0.16	-0.23	-0.09	-0.01	-0.06	0.03
Shrubland	0.05	0.03	0.07	0.08	0.06	0.09
Low vegetation	-0.02	-0.05	0.01	-0.04	-0.07	-0.02
Lakes	-0.05	-0.07	-0.02	-0.03	-0.06	0.00
Elevation	0.06	-0.11	0.23	-0.09	-0.15	-0.03
NDVI (normalized difference vegetation index)	2.06	-1.31	5.43	0.82	0.46	1.18
Distance to nearest coast	0.54	0.41	0.67	0.35	0.26	0.45
Distance to neatest infrastructure	-0.10	-0.36	0.16	0.30	0.14	0.45
Density around nearest infrastructure	3.57	0.77	6.37	-56.75	-79.91	-33.59
Distance to nearest infrastructure * Density	0.58	0.02	1.15	-12.45	-18.01	-6.89
Distance to neatest infrastructure * NDVI	-0.01	-0.75	0.73	-	-	-
Density * NDVI	-3.26	-7.63	1.11	-	-	-

B)

	RAF			RG		
		95% CI			95% CI	
Landscape attribute	β	Lower	Upper	β	Lower	Upper
Conifer forests with lichens	0.01	-0.01	0.03	0.02	-0.01	0.04
New or old disturbance (toundra fire)	-0.02	-0.05	0.01	-0.05	-0.10	-0.01
Open areas without lichens	-0.12	-0.21	-0.04	0.01	-0.06	0.08
Open areas with lichens	0.14	0.09	0.18	0.08	0.05	0.11
Lakes	-0.05	-0.07	-0.02	-0.04	-0.08	-0.01
Elevation	-0.05	-0.28	0.18	-0.42	-0.64	-0.20
Distance to nearest coast	-0.54	-0.91	-0.16	-0.32	-0.58	-0.05
Distance to neatest infrastructure	0.23	0.08	0.39	0.03	-0.13	0.19
Density around nearest infrastructure	-1.52	-8.58	5.54	11.44	0.60	22.27
Distance to nearest infrastructure * Density	-0.78	-2.24	0.67	2.19	-0.28	4.66

investigations for black bears on the Rivière-George herd calving grounds undertaken in June and August resulted in 19 and 24 clusters, respectively, being investigated. No caribou remains were found on any of these clusters, although all clusters were described for potential other behaviours (plant-foraging, bedding, etc.). Currently, there are limited results for this project as the first three months consisted of data collection, establishment of a clustering algorithm, and the identification of potential clusters. Analysis of habitat selection for both wolves and bears are beginning in January 2017 with further cluster investigations planned throughout the next two years.

Our second objective is to reconstruct the diet of wolves and black bears to determine the proportion of caribou on an individual, population, seasonal and annual basis for each species of predator. We initiated a sampling program involving Cree and Inuit trappers to collect various tissues of predators and preys. Samples of wolves, foxes and other preys

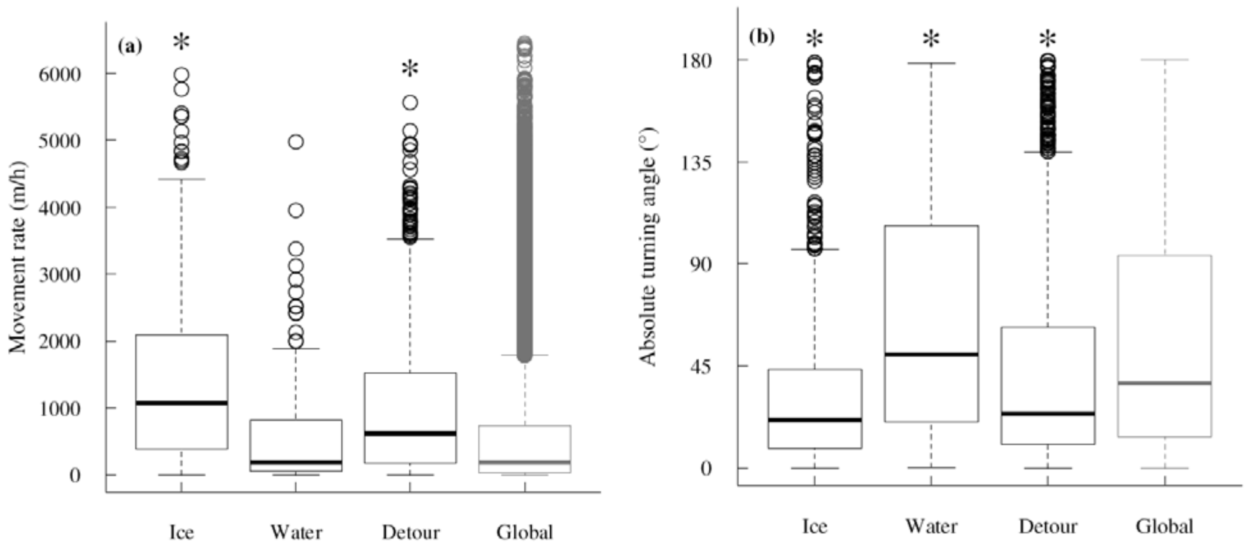

Figure 2. Movement rates (a) and turning angles (b) of Rivière-aux-Feuilles caribou across different substrates. Movements on and around water bodies are compared to movements elsewhere in the study area. Statistical differences from the reference category (i.e., Global) are indicated using an asterisk.

species have been collected through our different collaborations in the North. These tissues will be used to reconstruct the diet of predators through different methodological approaches; stable isotope analysis, identification of macro-remains and DNA barcoding (Milakovic and Parker 2011, Pompanon et al. 2012, Lesmerises et al. 2015). We continue to collect samples of predator tissues (Table 6) every time we capture and install a new satellite collar on a predator. We have collected 23 and 35 samples of feces of black bears from clusters of 11 black bears followed by GPS in Labrador in early July and mid-September, respectively. The samples of July will be analysed to identify macro-remains of caribou, especially calves as we suspect that black bear might be a key predator of calves survival on the calving grounds (Bastille-Rousseau et al. 2011, Rayl et al. 2015). We do not have results for this project as we still are in the sampling phase. We have started to analyse samples of hairs from black bears, but the results of isotopes will only be available in late January 2017. Much of the work of the last months was oriented toward the starting of the sampling program involving native hunters and trappers.

Objective 6. Indirect consequences of the intensification of the shrub layer on summer food resources of caribou: influence of snow and light attenuation (M.Sc. 2 – E. Lemay)

One of the evidences of global warming is the shrubification of the tundra in subarctic regions (Myers-Smith et al. 2011, Ropars and Boudreau 2012). Our objective is to determine the effects of increased snow cover and light attenuation by erected shrubs on the abundance and quality of caribou forage in summer. In July 2015, we implemented an experiment simulating snow interception and shading of ground layer vegetation by erected shrubs. We will conduct the experiment during four years at Deception Bay, Nunavik, within the summer range of the Rivière-aux-Feuilles caribou herd. The design is composed of nine blocks separated in two main plots receiving one out of two levels of the snow depth treatment (Figure 7). Beginning in spring 2016, we applied a two level shading treatment using a shading tarp in a subplot in each exclosure. From June 2016 onward, we automatically monitored environmental conditions

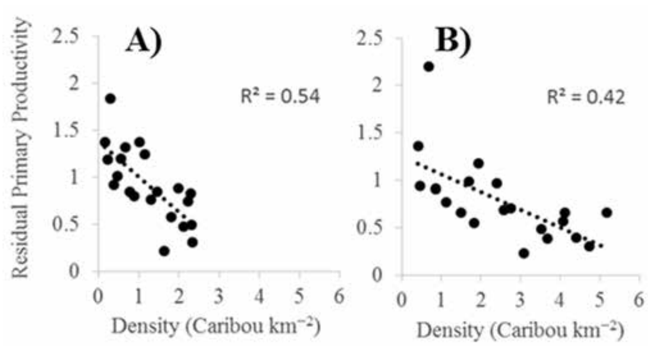

Figure 3. The negative relationships between caribou density and residual primary productivity for the global 1991-2011 summer range (A) and calving grounds (B) of the Rivière-George caribou herd.

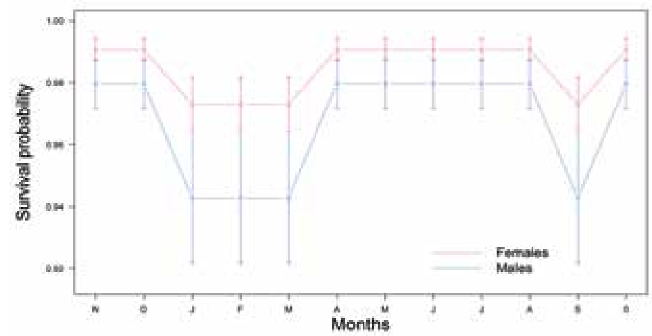

Figure 4. Monthly estimates of adult caribou survival from the Rivière-aux-Feuilles herd between November 2014 and October 2015.

in the experimental plots including snow depth, soil temperature and continuous estimation of the NDVI and the photochemical reflectance index (Figure 8). We estimated the biomass and composition of the plant community at t0 and we harvested foliar tissues from Betula glandulosa, grasses and *Carex* spp. to conduct analyses of their chemical composition.

DISCUSSION

Objective 1. Cumulative impacts of human disturbance on habitat selection and demography of migratory caribou (Ph.D. 1 – S. Plante)

Human disturbances have been suggested to be one of the main factors explaining the decline of caribou and reindeer populations (Vors and Boyce 2009). We are observing an increase in human disturbance in Arctic ecosystems, such as oil and mining exploitation, and we predict that the rate of increase of these activities may accelerate in the near future (CAFF 2013). Northern Québec and Labrador have already experienced a slight increase in industrial activities during the last decades. The region could be subject to a massive development in the next decades due to its strong mineral potential (Gouvernement du Québec 2013). This development could have major impacts on the ecology and demography of the migratory caribou. Most human disturbances trigger behavioral responses in wildlife that induce energetic costs, such as avoidance (Fahrig and Rytwinski 2009), but do not cause mortality directly. Sport hunting, however, is a particular type of disturbance where both behavioral responses and death can occur (Lone et al. 2015). In addition, the densification of human disturbances in the landscape is likely to intensify behavioral responses such as avoidance by caribou. In this context of northern development and industrialization, it is crucial to understand the effects of all potential sources of disturbances, especially for human activities that could cause caribou mortality, such as sport hunting.

Table 4. Yearly estimates of adult caribou survival from the Rivière-aux-Feuilles herd (RAF) and the Rivière-George herd (RG) between November 2015 and November 2016, including and excluding sport harvest effects.

Group	Harvest			No harvest		
	Survival estimate	Lower IC 95%	Uper IC 95%	Survival estimate	Lower IC 95%	Uper IC 95%
RG-F	0.78	0.66	0.86	0.91	0.81	0.96
RG-M	0.72	0.48	0.88	0.72	0.48	0.88
RAF-F	0.82	0.71	0.89	0.85	0.75	0.91
RAF-M	0.80	0.64	0.90	0.86	0.69	0.94

Table 5. Number of GPS collared wolves, black bears, and caribou with ranges overlapping that of the Rivière-George (TRG) and Rivière-aux-Feuilles (TRAF) caribou herds in northern Quebec and Labrador.

Year	Wolf		Black bears		Caribou	
	TRG	TRAF	TRG	TRAF	TRG	TRAF
2003	4	0	0	0	10	6
2010	1	0	0	0	24	44
2011	1	1	0	0	14	27
2012	4	7	10	4	6	20
2013	2	8	10	3	14	41
2014	1	3	12	1	31	30
2015	1	6	7	0	4	15
2016[1]	5	13	21	8	16	43

[1] Number of monitored individuals as of 11 December 2016

It is also important to assess the impact of the increase in disturbance density on caribou behaviour, but also on its survival. We showed that landscape characteristics better explain caribou vulnerability to sport hunting that caribou or hunters' behaviors. Our results suggest that accessibility to hunting grounds via roads and outfitter camps, and visibility were the main factors of vulnerability for caribou during sport hunting. Caribou were more vulnerable in areas accessible by hunters (near roads or camps) or offering good visibility (lakes, less rugged areas), but caribou tended to avoid these areas. Managers could use this information to manipulate hunting success by establishing minimal distance from infrastructures to which hunting would be prohibited. In addition, roads increase human access to remote areas. Further development in northern ecosystems could expand the area available to hunters and thus increase vulnerability of caribou.

Our preliminary results suggest that human disturbances can have single and cumulative effects on habitat selection behaviors of caribou. We showed, however, that these behaviors were highly variable through time and between herds. Part of this variation between herds may be attributable to population dynamics, and the distribution of disturbances and density on herds' ranges. Further analyses at other spatial scales are needed to conclude on the effects of human disturbances on caribou habitat selection. In addition, we do not know whether selection for disturbances could be detrimental for caribou. Thus, our final objective would be to evaluate the effect of habitat selection tactics on caribou survival.

Objective 2. Spatiotemporal use of migration corridors by caribou (Postdoc – M. Leblond)

The identification and protection of migratory routes is a major issue in the conservation of migratory ungulates (Wilcove and Wikelski 2008). Migrations allow large herbivores to exploit a wide spectrum of resources and to avoid predators during critical periods of their life cycle (e.g., during calving; Fryxell and Sinclair 1988). Migratory animals are usually well-adapted to variable environments, but the unprecedented rate of climate change may mislead animals into initiating their migration in suboptimal conditions. This may cause a mismatch between the timing of migrations and optimal environmental conditions, which may translate into higher energetic costs for locomotion (e.g., because animals need to walk in thick snow) or reduced survival (e.g., if animals drown after falling through ice too thin to bear their weight; Miller and Gunn 1986). We demonstrated that ice availability influenced the movements of a migratory arctic ungulate. Warmer air temperatures in the Arctic will undoubtedly modify the phenology of ice forming on freshwater lakes and rivers. If migratory caribou are unable to adjust the timing of

Table 6. Sample sizes for wolf and black bear tissues in the ranges of the Rivière-aux-Feuilles (RAF) and Rivière-George (RG) caribou herds since 2011.

Predator species	Herds	Hairs	Muscle	Blood	Stomach	Feces
Wolf	RAF	35	33	21	7	4
	RG	19	6	1	0	4
Black bear	RAF	16	16	15	0	2
	RG	72	46	56	0	58

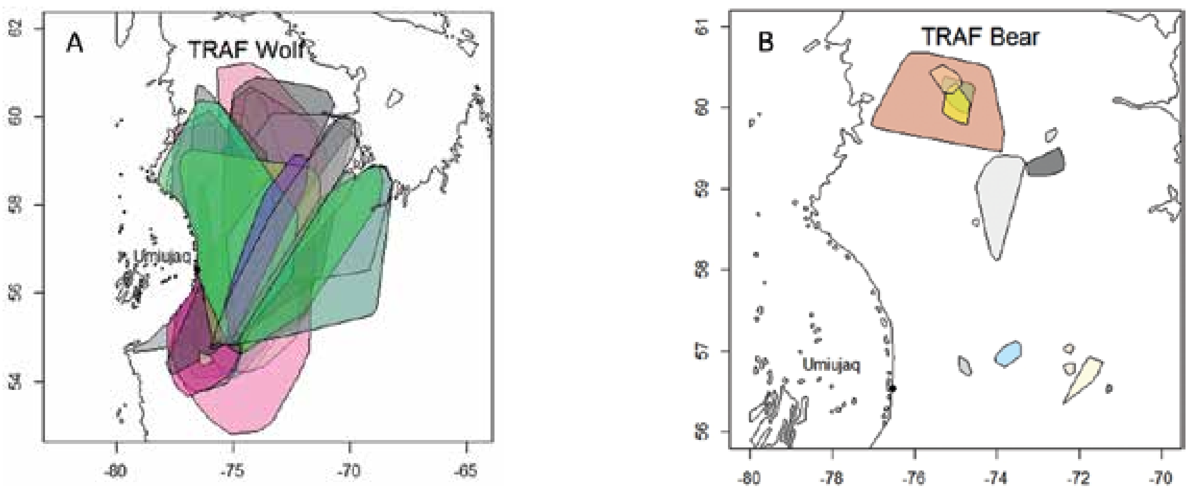

Figure 5. Home ranges of wolves (A) and black bears (B) located on the Rivière-aux-Feuilles caribou herd range, based on 95% Minimum Convex Polygons from 2011-2016.

their migrations, they could be forced to circumvent unfrozen water bodies more frequently and over broader areas, which may increase the distance, time, and energy they use to reach wintering areas. The long-term conservation of wide-ranging species will ultimately depend on our ability to identify the fine-scale behavioural reactions of individuals to broad-scale changes in climate and land use.

Objective 3. Evaluation of changes in space use of caribou using remote sensing (M.Sc. 1 – B. Campeau)

At high density, herbivory may be sufficient to reduce forage abundance, potentially contributing to habitat degradation and driving changes in herbivore population size or range use (Côté et al. 2004). Indeed, the exploitation ecosystem hypothesis (EEH) proposes that herbivory may have a dominant role in regulating plant biomass in low-productivity environments, like tundra and taiga, with forage abundance potentially limiting herbivore density (Oksanen et al. 1981). The migratory Rivière-George caribou herd has experienced a large decline in population size since the population peaked in the early 1990s, with similarly large changes in seasonal range use (Taillon et al. 2012). Demographic changes are suspected to have influenced forage abundance and caribou range use during the calving and summer foraging periods. Our study demonstrated that caribou herbivory can negatively impact the primary productivity of Arctic and subarctic terrestrial ecosystems, and that these changes may subsequently affect caribou population dynamics and space use tactics. We showed that caribou abundance is negatively correlated with cNDVI, our index of primary productivity, when the influence of climatic variation is removed. This was definitely the case for the Rivière-George herd global calving grounds and summer range. These results suggest possible support to the EEH, in the sense that caribou herbivory adversely affects the primary productivity of low-productivity environments in the absence of climatic forcing. However, climate warming in the area may reduce the future role of caribou herbivory in regulating primary productivity, and likewise reduce the potential for green forage abundance to limit the Rivière-George herd population size. The decline of the Rivière-George herd over the study period, along with the trend towards warmer summer temperatures and longer growing seasons, allowed for increases in primary productivity on the Rivière-George herd summer range and calving grounds. These range-scale increases in primary productivity probably represent increases in forage availability for caribou, and may therefore represent vegetation recovery following the decline in

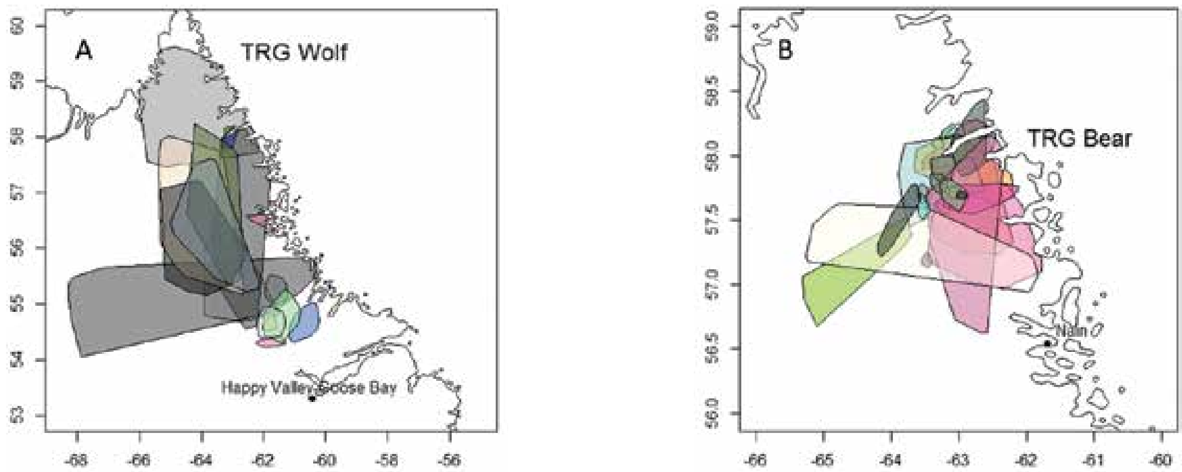

Figure 6. Home ranges of wolves (A) and black bears (B) located on the Rivière-George caribou herd range, based on 95% Minimum Convex Polygons from 2011-2016.

the Rivière-George herd population size and the associated decrease in caribou herbivory. However, climate warming could also contribute to changes in vegetation community composition, forage quality, and caribou diet that may offset the nutritional benefits of increases in green forage abundance (Zamin and Grogan 2013).

Objective 4. Determinants of annual caribou survival by age and sex (PhD 2 – B. Vuillaume)

To understand the dynamic of a population, we need information on survival and reproduction (Lebreton et al. 1992). In declining populations, such as the Rivière-aux-Feuilles and the Rivière-George herds understanding the causes of the decline is essential to manage effectively and maintain these populations. Preliminary analysis of the effects of hunting on survival rate showed that hunting could have contributed to the decline of the Rivière-George herd. For example, from November 2015 to November 2016, sport hunting explained 13% of the decrease in caribou female survival. Without this pressure on the female adult segment and assuming additive mortality, the survival rate could have allowed a slight increase of the herd. Regarding the Rivière-aux-Feuilles herd, the effect of hunting appears to be lower.

Despite adult survival is the demographic parameter with the greatest effect on population growth rate, juvenile survival can be an important component of population growth for caribou (Gaillard et al. 2000). Recruitment rate (number of calves for 100 females in November) is linked to juvenile survival and thereby to population sustainability and its capacity of growth. Low recruitment in several caribou populations is a concern. The analysis of the videos from the marked females should provide precious information on calf survival. We should be able to follow changes in environmental conditions throughout the summer range and to characterize the evolution of vegetation availability in the environments used. By associating information from videos to GPS location data and the analysis of changes in movement rate of females, we will identify accurately the moment of calf death.

Objective 5. Interactions between caribou and its predators (Ph.D. 3 – M. Bonin, Ph.D. 4 – R. Rogers)

While it is not always clear to what extent predators regulate prey populations (Brown et al. 1999; Bastille-Rousseau et al. 2011; Courbin et al. 2013), what is known is that predators almost always exert some sort of pressure on prey populations. Without fully understanding how predators control

Figure 7. An exclosure located downwind from one of the nine snow fences erected at Deception Bay, Nunavik, in July 2015 to simulate the indirect effects of the development of the shrub layer on snow interception and shading of ground layer plants (shading tarp visible on the left side of the exclosure). A second exclosure without a snow fence is also present at each experimental site (not visible on the picture).

prey populations, predation pressure coupled with increasing anthropogenic activities and human-induced prey mortality can lead to drastic changes in prey populations. This makes understanding the role of predation in predator-prey dynamics particularly important for the conservation of the migratory caribou of northern Quebec and Labrador. Both wolves and black bears are well known to be major predators of caribou (Ballard 1994, Dale et al. 1994). In northern Quebec and Labrador, however, some of these predators exhibit unique behavioural characteristics such as long-distance seasonal migrations (wolves) and occupation of barren-ground or tundra (bears). Quantifying the spatial and trophic interactions between predators and prey is crucial to broadening our understanding of the role of predation in community level predator-prey dynamics. Using a suite of spatial and demographic information and examining predator movement behaviour at multiple temporal and spatial scales, this work will help to better understand the dynamics of a complex ungulate specialist-omnivore multi-predator Arctic community. In addition, defining the feeding habits of the main predators of migratory caribou is a major step in order to understand the role of predation as a potential cause of decline of caribou herds. This part of the project will lead to the first description of the diet of wolves and black bears in northern Québec-Labrador and will improve our comprehension of the impacts of predation on the decrease of migratory caribou.

Figure 8. Instrumentation of plots using spectral reflectance probes (SRS, Decagon, Pullman, WA, USA) which allow continuous estimation of the standardized difference vegetation index (NDVI) and the photochemical reflectance index (PRI).

Objective 6. Indirect consequences of the intensification of the shrub layer on summer food resources of caribou: influence of snow and light attenuation (M.Sc. 2 – E. Lemay)

The experimental design required to meet objective 6 is now functional. However, we still need to make some adjustments to the design of the shading tarp to maximize shading on the underlying plot given the low sun angle observed at high latitudes. These changes will be developed during winter 2017 and implemented in June 2017. We will conduct additional measurements during the 2017 growing season. We will correlate the NDVI and PRI indices with the biomass of the main plants and their constituents (nitrogen, carbon, fibres, tannins) to develop phenological curves of macronutrients availability in the plants for caribou (Robbins et al. 1987, McArt et al. 2006). We recruited a master student (E. Lemay) for this project; she will officially begin in fall 2017, although she will conduct field work for this project next summer. This project will increase our understanding of the effects of increasing erected shrub on tundra vegetation used as forage by migratory caribou in summer.

CONCLUSION

Caribou are a crucial component of the ecology, economy and culture of the Arctic, and most Arctic herds are currently declining (Vors and Boyce 2009). It has been hypothesized that climate change and anthropogenic disturbance may be responsible for caribou declines, but little scientific evidence is available. With their high mineral potential, northern Quebec and Labrador are likely to see a major increase in industrial activities in the near future. These developments could have significant ecological and demographic impacts on caribou. Our research addresses a fundamental need of conservation in the Arctic by examining the factors affecting space use and population dynamics of migratory caribou. Our work is providing crucial information on the cumulative impacts of climate change and anthropogenic disturbance, including hunting, on caribou population size and its habitat. It will also allow predictions of further range use and population size of caribou that will be crucial to maintain sustainable subsistence hunting and possibly allow the return of sport hunting.

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BIOLOGY OF THE THREE MORPHOTYPES OF ARCTIC CHAR IN THE NETTILLING LAKE SYSTEM: DEVELOPING SUSTAINABLE COMMERCIAL AND SUBSISTENCE FISHERIES IN NUNAVUT'S TWO LARGEST LAKES

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ABSTRACT

In 2013 Expedition Q – a group crossing Baffin Island using traditional sea kayaks – discovered a previously unknown arctic char migration on the Amadjuak River which flows from Amadjuak Lake into Nettilling Lake to the North. Nettilling Lake is the biggest lake in the Eastern arctic and is the sixth largest lake in Canada. It is has both sea-run and resident char within its waters. The subpopulation of sea run char is estimated to be the largest in Nunavut; no estimates of the resident char population have ever been made. Nettilling Lake also has the largest commercial quota in Nunavut, none of which is being harvested due to a lack of economic viability. The discovery that substantial numbers of char migrate south enriches our knowledge of this ecosystem, and raises the possibility that a viable winter fishery could be established that would supply the currently underserved Iqaluit market. Every summer from 2015-17 an Iqaluit-led expedition is being mounted to gather biological samples of the char in the river. The team will also tag arctic char, and their movements up and down the river will be recorded by monitors moored at key choke points throughout the river. Every winter a second expedition will be mounted to explore the many small frozen lakes along the southern shore of Amadjuak Lake to look for and tag char at their furthest point of migration – which also happens to be the closest point to char-hungry Iqaluit. The results from this project will inform future efforts to understand and sustainably manage the Amadjuak and Nettilling Lake winter fisheries.

KEY MESSAGES

The second year of fieldwork was a complete success for the "Biology of the three morphotypes of Arctic charr in the Nettilling Lake system: Developing sustainable commercial and subsistence fisheries in Nunavut's two largest lakes".

All but one of the 14 acoustic telemetry receivers were recovered in good condition and downloaded after a one year deployment. A total of 12 were re-deployed (five at the mouth of Koudjuak River in Lake Nettilling and seven throughout the Amadjuak River) to record any tagged fish moving to and returning from the ocean/Amadjuak River from fish tagged in 2014, 2015 and 2016.

A total of 302 fish of all three morphs were caught and sampled in 2016, 45 were released with an acoustic tag following taking a fin clip for stable isotopes and genetic analysis and morphometric measurements. A high percentage of tagged Arctic Char were detected on receivers recovered in 2016, demonstrating that acoustic telemetry is an excellent method for studying Arctic Char movements and behavior in remote lake and river systems. Preliminary results show distinct movement patterns between morphs with large, mature female "orange" and some "silver" morphs make the 200 km one-way migration from Amadjuak River through Lake Nettilling and into the ocean and return 51 days later. "Green" morphs appear to be highly residential within Amadjauk River, are smaller in size, reproductively "resting" – mature but not spawning that year – and filled with parasites. Also, preliminary genetic results show very high levels of genetic structuring in the Lake Nettilling Arctic Char, indicative of extensive reproductive isolation.

With only some basic or preliminary analyses completed to date, there already is morphological, genetic, and movement differences amongst the suggested, observable morphotypes. Further analyses of this data combined with stable isotope, stomach contents, aging, and mercury will uncover ecological details of the observed morphotypes. This multi-disciplinary approach has been important for disseminating the differences amongst the morphotypes and will translate into effective management efforts towards developing a viable and sustainable commercial and subsistence fishery on Lake Nettilling as well as uncovering interesting biological information on Arctic Char in this unique and remote system.

OBJECTIVES

This project has three major objectives:

Objective 1 – ***Collect basic biological data and archive samples***. Given the lack data of data or samples from this unique system, (no sampling undertaken between 1977 and 2014), there is a need to collect basic information (length, weight, structures for age determination (otoliths), sex, state of sexual maturity, fecundity, colour, parasite loads, and tissue samples) on the Arctic Char. In addition to the food web ecology objective below, we will endeavour to find additional financial resources for future genetics studies.

Objective 2 – ***Understanding the feeding ecology of Nettilling/Amadjuak system Arctic Char***. Given the unique prey base in this system and the different morphotypes we will measure stable isotopes in liver and muscle tissues of the three Arctic Char morphs collected in the two large lakes and the river (and biopsies of tagged fish). Turnover rates of stable isotopes are faster in liver and give a more recent evaluation of feeding (3-6 months), whereas muscle integrates diet over 6-12 months. Prey samples will also be sampled to estimate char diet using Bayesian based mixing models (Parnell et al. 2013), and isotopic niche widths will be used to examine potential competition for resources.

Objective 3 –***Determine the timing, extent and dynamics of the movements and migration of char in the Nettilling/Amadjuak system.*** Complementing the basic biological information and feeding ecology, data on the movements of tagged individual char will provide key insights into specific behavioural strategies of the morphotypes, and will contribute towards an understanding of the population dynamics and interplay between anadromous and non-anadromous Char.

KNOWLEDGE MOBILIZATION

Examples of Knowledge Mobilization activities undertaken to disseminate research results:

- Two presentations at scientific conferences (ArcticNet 2016 and Canadian Conference of Freshwater Fisheries Research 2017).
- Three scientific papers in preparation, one undergraduate research thesis, one MSc thesis.
- Mentoring of undergraduate students at University of Windsor.
- Provide mentorship and skills training to Iqaluit based social enterprise Project Nunavut Ltd and Expedition Q.

INTRODUCTION

The Arctic Char (*Salvelinus alpinus*) is the most harvested species of wildlife in Nunavut (Priest and Usher 2004), represents a culturally important species and is used by Inuit across the territory for both subsistence and commercial purposes. The Federal Government and the Government of Nunavut have both identified the development of commercial fisheries for anadromous (i.e., searun) Arctic Char as a priority because it provides a sustainable and culturally meaningful opportunity for economic development (Government of Nunavut and NTI 2005; Rompkey and Patterson 2010). Commercial fishing for Arctic char currently generates approximately $1.4 million annually and employs a large percentage of Nunavumiut both seasonally and permanently in most communities (Government of Nunavut and NTI 2005). Within the Canadian Territories the current demand exceeds the available supply by approximately threefold. By numbers Char is the most harvested animal in Nunavut and every community utilizes Arctic Char.

Nettilling Lake, the largest lake in Nunavut and the largest found on an island in the world, has the largest commercial Char quota in the Eastern Arctic at 22,700 kg (Kristofferson et al. 1991). The Nettilling Lake fishery has been dormant since at least 2001 due to the high cost of air transportation of harvested char back to Iqaluit by Twin Otter airplanes (Janelle Kennedy, personal communication). Nettilling Lake is connected to the ocean (Foxe Basin) to the west by the Koukdjuak River, and to the large Amadjuak Lake to the south via the Amadjuak River. Amadjuak Lake has its own Char quota of 9,100 kg, but this quota has never been active because the Char population is considered to be landlocked and thus vulnerable to exploitation. It is also thought to be of lesser value due to high parasite loads (Popko 1980, Kristofferson et al. 1991). In August of 2013 and 2014, previously unknown Arctic Char migrations were documented in the Amadjuak River and the north end of Amadjuak lake that included all three known morphs (landlock green, anadromous orange and anadromous silver) (William Hyndman, unpublished data). This strongly suggests that anadromous char may be present in Amadjuak Lake opening the possibility of a fishery that is closer to Iqaluit and consequently more economically viable. Amadjuak is close enough to Iqaluit for a viable winter subsistence or commercial ice-fishery, and even southern Nettilling Lake could be a possible fishery if the catches of char were reliable. These findings also support the development of a recreational or charter-based summer fishery.

In addition to the obvious fishery opportunities that Lake Nettilling/Amadjuak offers, there are many unanswered questions over the general biology and ecology of Arctic Char in this unique freshwater system, particularly relating to the different morphotypes. Lake Nettilling is 111 X 97 km across, making it the 6th largest lake in Canada. The lake has a maximum depth of 132 m and ~74% of the lake is deeper than 20 m with a west region that is deeper with few islands and a shallower region to the east that has numerous islands of various sizes (Oliver 1964). Ice starts to break up in July, mainly at the river mouths with surface temperatures > 7 °C in August. The ice reforms in late September and early October, with ice varying in depth between 1.5 and 1.9 m at its maximum (Oliver 1964). In addition to char, the lake supports populations of Threespine (*Gasterosteus aculeatus*) and Ninespine (*Pungitius pungitius*) stickleback fish and significant numbers of ringed seal (*Pusa hispida*). Interestingly, the lake supports large populations of chironomid larvae populations of other invertebrates (e.g., amphipods and molluscs) are much smaller. This contrasts most arctic lakes in the region where invertebrates are typically much more abundant than Chironomids (Oliver 1964). The unique diversity of potential prey in Lake Nettilling may represent an atypical diet for these Arctic Char, which could explain proposed higher growth rates of both anadromous and non-anadromous morphotypes in this system (Kristofferson et al. 1991). Given the two colours of anadromous morphotypes, questions remain about the relative importance of lake resources and whether the potentially large food base of this lake explains the abundance of the different morphs. Given this, we hypothesize that the anadromous "silver" morphotypes (anadromous char were identified by smaller heads and bigger bodies), that are more similar in colouration to the landlock morhotypes, have a greater reliance on lake production than orange morphotypes?

Despite their cultural and commercial importance, relatively little is known about the marine and freshwater migrations of Arctic Char for any system (Roux et al. 2011). Anadromous Arctic Char migrate to the marine environment during ice breakup to feed, before returning to the freshwater in the fall to spawn. There exists a wide range of possible movement and migration strategies of Arctic Char in the Nettilling/Amadjuak system given the complexity of the ecosystem that includes a number of rivers, two large lakes, and potentially numerous smaller lakes. As well, recent acoustic telemetry work in Cambridge Bay, has questioned the paradigm of this distinct marine/freshwater finding that searun Arctic Char can make numerous movements into freshwater during their marine phase, and these can include movements into systems that are not natal (Jean Sebastian Moore, unpublished data).

Given the colour types in the two anadromous morphs, could orange individuals spend more time at sea? Do the three morphotypes have variable movement behaviors in the system and/or do they choose unique spawning locations? Given the lack of basic information on these Arctic Char populations, a first step to ensure sustainable harvesting if fisheries developed is to understand their large-scale movements patterns. This would include the times fish leave and return from the ocean and the times of movement within winter residency locations between the two large lakes and numerous lakes of the Amadjuak River.

In August of 2014 an exploratory trip to the Nettilling/Amadjuak system was undertaken to initiate studies on the movement, feeding ecology of these Arctic Char morphs. This highly successful field expedition deployed a preliminary acoustic telemetry array in the Amadjuak River, the north end of Amadjuak Lake and the south end of Nettilling Lake, surgically implanted acoustic transmitters (also called tags, Vemco V13 1L and V16 4H) in 42 Arctic Char of all three morphotypes as they migrated up the Amadjuak River, and took fin clippings from 45 individuals for stable isotope and genetics analyses. The acoustic tags produce a tag specific communication that is recorded when within range of an acoustic receiver (~ 1 km). The tags were programmed to communicate approximately every 3 minutes for up to 4 years (duration of this proposed project). The receiver array, deployed for a full year (to be collected in August 2015), was designed to determine how far up the river the tagged fish travel, if they progressed to Amadjuak Lake, and when/if the fish return to Nettilling Lake.

This proposal seeks to return to the Amadjuak River in each of the next three summers (2015-2017) to download, service, maintain and redeploy the acoustic monitor array and importantly to expand its spatial scope and increase the number of tagged fish in the system. We will also collect more tissue samples (include potential prey samples and biopsies from tagged fish) for stable isotope analysis to examine intra and inter-specific feeding behaviours among morphs. Thus, we will apply a multidisciplinary approach integrating traditional knowledge of the area with acoustic telemetry and feeding ecology using stable isotopes. Our study will address key challenges in the future management of this fishery, provide crucial information on critical freshwater and marine habitats, and establish a basis for understanding the ecological factors that will be most important in predicting the response of Arctic char to a changing Arctic. These goals align with the ArcticNet target research goals #5 Impacts of climate shifts on marine and terrestrial ecosystems and their services and #11 Food and water security in northern communities.

ACTIVITIES

The August 2016 field season was a complete success. Two trips were made to the Lake Nettilling and Amadjuak River system:

1. Trip 1: A team of six people (four team members from the Government of Nunavut, a local Inuit harvester, and a member University of Windsor) travelled by Twin Otter to the Environment Canada Field station near Koudjuak River on Nikku Island. The team gillnetted and lethally sampled 155 Arctic Char for biological and morphometric information, and collected fin, liver, gill and muscle for genetics, stable isotopes, and mercury analyses. The team also collected nine Ninespine Stickleback via minnow traps and conducted a zooplankton tow for stable isotopes. Using a small zodiac boat, five of six receivers were retrieved (one lost its mooring). Telemetry data was downloaded and the five receivers were re-deployed in a slightly different array based upon preliminary data analyses. A set of sync tags were also deployed to determine the range detection of the tags throughout the year. Complementing the sync tags, an activated tag was towed by boat to get further information on range detections. These receivers and range testing will provide information on which tagged char move to the ocean. With the available time, one fish was tagged and released alive.

2. Trip 2: Was a 12-day rafting trip from Lake Amadjuak to Lake Nettilling via Amadjuak River by a team of five people (three employed by the Government of Nunavut and two employed by University of Windsor), brought and retrieved by Twin Otter flights from Iqaluit (covered by PCSP funds). The team retrieved all eight receivers from 2015, downloaded the data and re-deployed the receivers. At some locations, receivers lost their moorings and re-deployment locations changed to prevent this from occurring again as well as deploying in a potential overwintering location based on information from local Inuit knowledge. A total of seven receivers were re-deployed. Two sets of sync tags were deployed to determine the range detection of the tags throughout the year in the river environment. A total of 147 fish were sampled in which 44 were released alive tagged (fin clip taken) and 102 were euthanized and sampled for fin, liver, gill and muscle for stable isotope and genetic analyses. All euthanized fish had a full morphometric analysis.

Tissues samples have been shipped to the University of Windsor for stable isotope analysis, which have begun (expected completion date April 2017). Tissues have also been provided for a genetic analysis of the three different morphs. Liver and muscle tissues were sent to McGill University for mercury analysis (Lake Nettilling fish only). Otoliths are to be sent to DFO for aging and stomach contents are to be analyzed by Government of Nunavut. Telemetry data is currently being analyzed and needs to incorporate detection ranges based upon range test data that is being assessed. This analysis is expected to be completed by April 2017 and will provide insights on the quality of data collected and the need for further monitoring beyond 2017.

RESULTS

A total of 302 fish of all three morphs were caught and sampled in 2016, 45 were released with an acoustic tag following taking a fin clip for stable isotopes and genetic analysis and morphometric measurements. All but 1 of the 14 receivers were recovered in good condition and downloaded, and 12 were re-deployed (five at the mouth of Koudjuak River in Lake Nettilling and seven throughout the Amadjuak River) to record any tagged fish moving to and returning from the ocean/Amadjuak River.

Based on preliminary analyses, some general trends were seen in terms of morphology, parasite loads, and sex and reproductive maturity for a subsample of 2016 fish sampled in the Amadjuak River. In terms of size based on standard length, the “orange” morph is the largest, followed by the “silver” morph and the “green” morph being the smallest (Table 1). There also appeared to be a trend of the presence of parasite being greater in “green” morphs (85%), with fewer in “silver” morphs (67%), and hardly any in “orange” morphs (15%). However, note that this was anecdotal evidence and recording of parasites was not necessarily consistent. In terms of reproductive maturity, all “orange” morphs were mature, with 85% of fish investing energy into spawning (gonads were not in a “resting” stage where they were mature but not spawning that year). The majority of “green” morphs were mature (95%), yet 65% of the fish were in a “resting” stage. While all the “silver” morphs were reproductively immature. Also, something to consider, the morphs had an equal sample of males and females, except for the “orange” morph in which 95% of the subsampled fish were females.

A total of 146 fish have been tagged to date. From the 42 Arctic Char acoustically tagged in 2014 (prior to the beginning of this ArcticNet funding), 34 were detected by the receivers in 2015 (81%) with only 16 detected by receivers in 2016 (38%; Table 1). Of the 66 Arctic Char tagged in 2015, 46 were detected by receivers in 2016 (70%; Table 2). A greater proportion of “green” morphs were detected in 2015 as opposed to 2016 and this may be due to tagging and releasing fish near a receiver in 2014 and not doing so in 2015, and the potential for residency by “green” morphs. Some level of residency is also suggested with the high number of detections made by a few fish at the upper section of the Amadjuak River in 2014 (which were all "green" morphs; Figure 1). Currently, there is very little overwintering data on the Arctic Char with a few individuals being detected at the mouth of the Koudjuak River and in the lower portion of the Amadjuak River (Figure 1). Also, only one fish was detected at the Amadjuak Lake gate, yet there was no indication that it moved into Amadjuak Lake. It appears as though fish in Amadjuak Lake may be distinct from Lake Nettilling/Amadjuak River fish. While taking into consideration that more fish were tagged throughout the study period, there is a high number of individuals with few overall detections occurring in July 2015 and 2016 as well as September 2015 suggesting lots of movement (e.g., migration; Figure 1). Of particular note is the large number of fish detected passing the receiver gates towards the ocean in July 2016. With the timeline of receivers being deployed at the mouth of Koudjuak River, a full migration both to and from the ocean has yet to be detected. However, of the fish tagged in 2014 – half of the fish moved into Lake Nettilling (53%) with half of those being detected returning from the ocean (Figure 2). Fish tagged in 2015, with a greater proportion of "orange" morphs tagged, had nearly all fish move into Lake Nettilling (mostly "orange" morph with some "silvers"; 91%), and just over half of those making the trip into the ocean (Figure 3). No "green" morphs left Amadjuak River, further suggesting residency within the river. Timing of moving into the ocean appears to be late June/July and moving back from the ocean appears to be September/or early October and spending an estimated average of 51 days (1.5 months) in the ocean. The distance between the ocean from Amadjuak River is roughly a 200 km migration. Returning from the ocean to the river took an average of 6 days – ~33 km/day. While travel to the ocean from the river took an average of 11 days - ~18 km/day. Of fish returning from Lake Nettilling into Amadjuak River, no fish moved upstream of the Amadjuak Rapids, even though some of the out-migrating fish were tagged above the rapids.

There was some indication that detection efficiency was not absolute. Some fish were not picked up at receivers that they swam past and were detected at other receivers. The level of detection efficiency is to be determined with further data analyses. Also, the level of interference with ice has yet to be quantified. There appears to be some interference in range detection with ice formation. However, some of the receivers that lost their moorings and floated to the surface became entrapped in ice, yet still managed to detect a fish. Thus, determining the impacts of ice in the river on detection efficiency and range will be important.

To further understand the suggested morphotypes, genetic analyses were undertaken. As Lake Nettilling Arctic Char are known to display highly diverse morphotypes as suggested based on colouration and size (as indicated above), and based on char phenotypic variation in other systems, it is likely that the variation in Lake Nettilling is due to reproductive isolation and genetic divergence. Using the collected fin clips for DNA (and liver/gill tissue for mRNA) from 2014 and 2015, we optimized 10 microsatellite markers to test for reproductive isolation. Preliminary results show very high levels of genetic structuring in the Lake Nettilling Arctic Char (Figure 4), indicative of extensive reproductive isolation. Analyses will continue for the 2016 samples and we will continue to refine the population genetic analyses and prepare for RNA sequencing (RNA-Seq) to identify the functional

Table 1. The mean, standard deviation (SD) and range of standard length of a subset of Arctic Char (Salvelinus alpinus) based on colour morphology sampled in the Amadjuak River, Baffin Island, 2016. Sample size is indicated by n.

Morph	Mean ± SD (mm)	Range (mm)
Orange (n = 20)	570 ± 60	488 - 698
Silver (n = 6)	473 ± 109	383 - 664
Green (n = 20)	421 ± 71	295 - 592

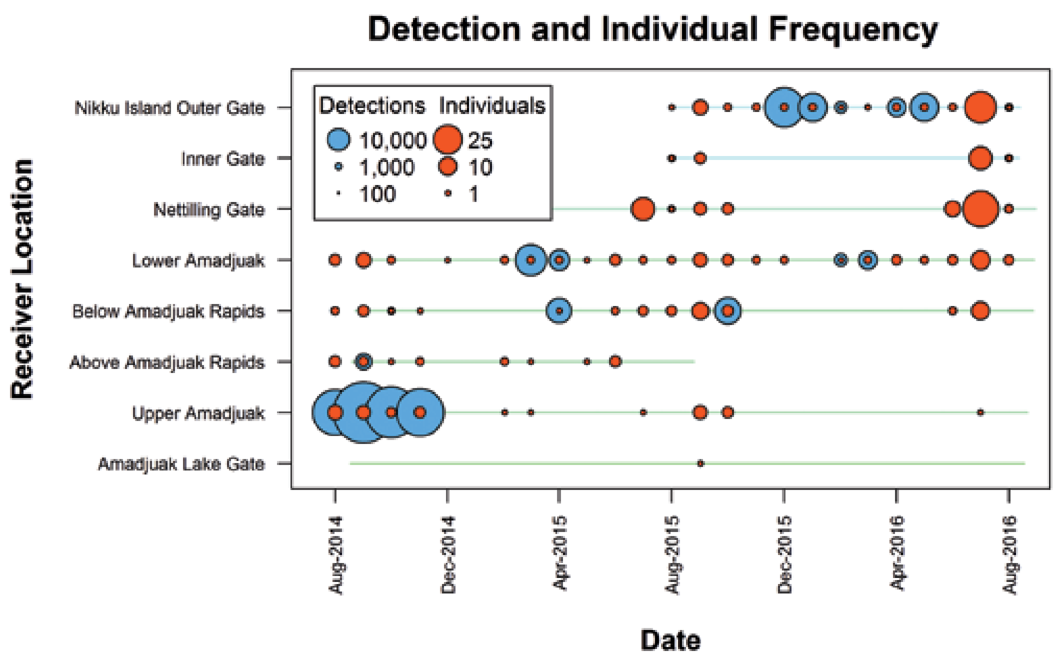

Figure 1. The number of detections (number of times a receiver picked up a fish within its vicinity) and number of tagged individual Arctic Char throughout the acoustic receiver array over time. The receiver location follows a south-north gradient, from Amadjuak Lake north to Lake Nettilling and then towards the ocean (Nikku Island Outer Gate is the closest group of receivers to the ocean). Horizontal lines associated with receiver groups over time indicates the duration of deployment/ability to detect fish in that location.

Table 2. The number and proportion of Arctic Char tagged with acoustic transmitters in August 2014 and were detected within the acoustic receiver array from August 2014 to August 2015 (2014-2015) as well as the following year from August 2015 to August 2016 (2015-2016). Tagged fish are separated into groups based on observable colour morphotypes; unknown fish were not designated to any morphotype.

		Tags Detected			
		2014-2015		2015-2016	
Morph	**Tagged 2014**	**Number**	**Proportion of Tagged**	**Number**	**Proportion of Tagged**
Green	9	8	0.89	0	0.00
Orange	18	14	0.78	8	0.44
Silver	3	1	0.33	1	0.33
Unknown	12	11	0.92	7	0.58
Total	**42**	**34**	**0.81**	**16**	**0.38**

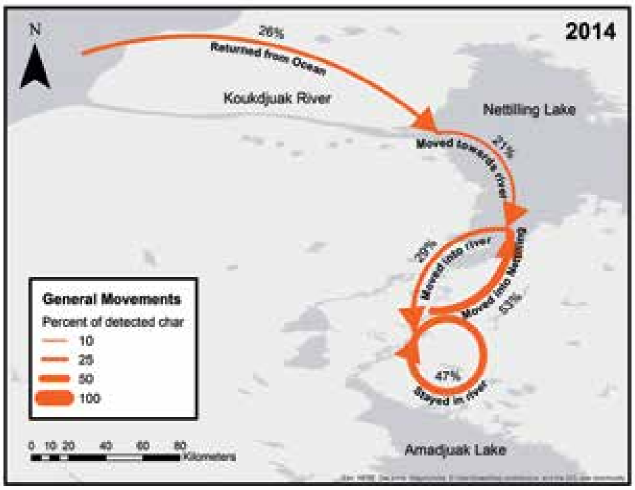

Figure 2. The general movements of Arctic Char tagged with acoustic transmitters in August 2014 in Amadjuak River. Movement percentages are based upon the number of fish detected moving past certain receiver gates divided by total fish detected. Some fish will fall into multiple movement categories as such values do not all add to 100% - example – a fish moves into Lake Nettilling and also moves back into Amadjuak River and counts towards both those movements in the percentages. Movement into the ocean could not be determined based on the date of deployment of the receivers at the mouth of the Koudjuak River.

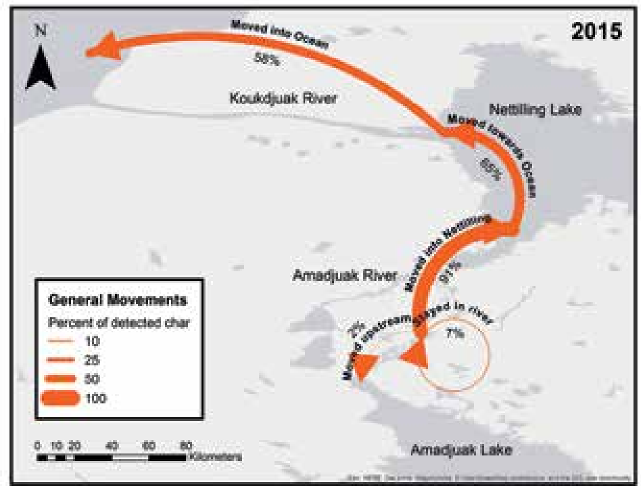

Figure 3. The general movements of Arctic Char tagged with acoustic transmitters in August 2015 in Amadjuak River. Movement percentages are based upon the number of fish detected moving past certain receiver gates divided by total fish detected. Some fish will fall into multiple movement categories as such values do not all add to 100% - example – a fish moves into Lake Nettilling and also moves back into Amadjuak River and counts towards both those movements in the percentages. Movement out of the ocean and into the river could not be determined based on downloading the data in August 2016 while fish are likely still in the ocean.

differences among the morphotypes. Also, the results of the genetic structuring have yet to be compared to the morphological type and it is unknown if the separate genetic structures matches the observable morphotypes.

Morphometric, stable isotope, and telemetry data are being analyzed with aging, stomach contents, and further genetics to still be processed.

DISCUSSION

Year 2 of this project continues to bring exciting results. All but 1 of the 14 receivers deployed in August 2015 were recovered in August 2016, and we now have 2 years of telemetry data. Given the high flow and unknown ice characteristics of this system this is a remarkable achievement given the receivers were deployed at depth for 12 months. Of note, this is the first use of a new Vemco acoustic receiver with a built in acoustic release. These built in receivers save space, weight and money, the fact they worked so well opens up new opportunities for research in remote and hostile places.

We are starting to disseminate the biological data and have noticed some trends between the different morphotypes. Based from a subset of 2016 data, it appears that "orange" morphs are large, preparing to spawn, females with few parasites; "green" morphs are small, reproductively mature but resting, with lots of parasites; and "silver" morphs are intermediate in size, reproductively immature. Although this raises the question of whether we are observing differences among sexually mature and immature fish from the same population. However, the genetics disputes this with indications of at least 3 morphotypes that are reproductively isolated.

Telemetry data also suggests some variation between the different morphotypes. Initial results are consistent with our expectations, bright "orange" morph Arctic Char move into Lake Nettilling, with roughly half of them continuing on into the ocean. Some "silver" morphs also move into the lake and towards the ocean while others stay in the river. However, the "green" morph appears to be quite residential and restricted to the Amadjuak River. Detections of "green" morphs were sparse for 2015 and was likely due to releasing tagged fish close to receivers in 2014 but not in 2015. Thus, there is the potential that "green" morphs exhibit a much higher level of residency within a particular river reach which was picked up in the 2014 data. Of the fish sampled in the Amadjuak River, there was no indication of movement into Lake Amadjuak and fish within Lake Amadjuak likely represent its own population (with unknown information on morphotypes). Although it appears that fish overwinter within the Amadjuak River or surrounding lakes, there is currently no information on whether Char overwinter in a specific area in the system or sparsely throughout. Information based on local Inuit harvesters indicates that Arctic Char may be overwintering in some of the small lakes connected to the Amadjuak River. Deployment of a receiver in one of these said lakes should provide answers and may aid in the development of a winter Arctic Char fishery.

With further analyses of stable isotopes, stomach contents, age, and mercury, we aim to determine which morphs are utilizing ocean food webs or stay within the freshwater system and the management repercussions associated with these morphotypes. There are already observed differences between the morphotypes but elucidating whether the morphotypes are reproductively isolated and should be treated separately for fisheries management purposes is an important goal. Currently, with the preliminary genetic results, the levels of genetic divergence seen in the Arctic Char should lead to special management efforts to identify the populations and manage them separately. Also, taking in consideration Inuit commercial harvester's standpoint that there is little value in the "green", parasite loaded morphs and a greater preference for the "orange" parasite-free, ocean run morphs. However, if "orange" morphs tend to be primarily female, this also has fisheries management repercussions. Determining the biological nuances amongst the different observable morphotypes and correlating movement patterns will help elucidate whether a viable fishery can occur in Lake Nettilling and management strategies to ensure the Arctic Char fishery is sustainable without detriment to the population.

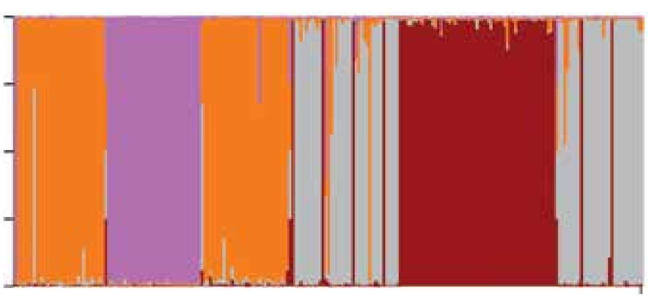

Figure 4. Barplot of Nettilling Lake Arctic Charr genetic structure assayed using STRUCTURE (K = 4). The different colours correspond to genetically distinct clusters based on data from eight microsatellite loci and >200 fish sampled in 2014 and 2015.

Table 3. The number and proportion of Arctic Char tagged with acoustic transmitters in August 2015 and were detected within the acoustic receiver array from August 2015 to August 2016 (2015-2016). Tagged fish are separated into groups based on observable colour morphotypes; unknown fish were not designated to any morphotype.

		Tags Detected 2015-2016	
Morph	**Tagged 2015**	**Number**	**Proportion of Tagged**
Green	18	2	0.11
Orange	37	35	0.95
Silver	9	7	0.78
Unknown	2	2	1.00
Total	**66**	**46**	**0.70**

CONCLUSION

With only some basic or preliminary analyses completed to date, there already appears to be morphological, genetic, and movement differences amongst the suggested, observable morphotypes. Further analyses of this data combined with stable isotope, stomach contents, aging, and mercury will uncover ecological details of the observed morphotypes. This multi-disciplinary approach has been important for disseminating the differences amongst the morphotypes and will translate into effective management efforts towards developing a viable and sustainable commercial and subsistence fishery on Lake Nettilling as well as uncovering interesting biological information on Arctic Char in this unique and remote system.

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MONITORING AND MANAGING MUSKOX HEALTH FOR FOOD SECURITY AND ECOSYSTEM AND SOCIO-ECONOMIC RESILIENCE: INTEGRATING TRADITIONAL, LOCAL, AND SCIENTIFIC KNOWLEDGE

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ABSTRACT

Muskoxen are integral to the culture, food system, economy, and ecosystem health in the Arctic. In recent years, widespread mortalities of muskoxen on Victoria and Banks Islands, with concomitant population declines, have raised concerns about the health and sustainability of these animals. Additionally, sick and declining muskox populations will increase the already substantial food insecurity concerns across the Canadian North. Our work aims to (i) determine the current health status of muskoxen in increasing and decreasing populations of muskoxen in the Inuvialuit Settlement Region and Kitikmeot region, (ii) evaluate the factors which influence health, including disease, contaminants, climate, disturbance, and stress in these differing populations, (iii) investigate the ecology of muskox diseases, including three recently emerging diseases, through scientific study and examination of Traditional Ecological Knowledge and Local Expert Knowledge, (iv) develop key indicators of health that can be incorporated into muskox monitoring programs, and (v) establish and implement an integrative and responsive muskox health surveillance system that is used to pro-actively inform wildlife management, public health, and land-use policy and decisions. We will work closely with communities of the Inuvialuit and Kitikmeot regions to do this research and develop and implement the surveillance program. There will be extensive training of northerners, as well as youth, graduate and undergraduate students through formal and informal classroom and on-the-land experiences. Our partners include local, regional, and territorial wildlife hunter and trapper organizations, industry, government, academia and local resource users. Ultimately we will use a combination of scientific, traditional and local knowledge and engagement to evaluate and monitor the health and vulnerability of muskoxen in a rapidly changing Arctic. Tools, techniques, and programs developed, together with extensive training of both northerners and southerners, will lead to improved technical and human resources for wildlife health monitoring and enhancement of food security across the North.

KEY MESSAGES

- Climate change and other ecological changes are affecting the health of wildlife in northern ecosystems.
- Muskoxen have a nutritional, socio-cultural, economic and environmental importance. The recent declines of muskoxen have had significant and multiple impacts on the local economy, food security, as well as socio-cultural dimensions.
- Our work in 2016-17 suggests that health of muskoxen in the western Arctic Archipelago is declining and that they may have low resilience to ongoing environmental changes and challenges due to new pathogens.
- Traditional and local knowledge (TEK/LEK) collected in 2014-16 indicate muskox populations have been declining since the mid-2000s, with smaller group sizes, fewer young animals, increased mortality and poorer body condition in the area of Ikaluktutiak (Cambridge Bay, Victoria Island, NU).
- The lungworms, *Umingmakstrongylus pallikuukensis* and *Varestrongylus eleguneniensis*, first detected on Victoria Island in 2008 and 2010, respectively, have expanded their range on the island. *Umingmakstrongylus* is now found as far north as Ulukhaktok; *Varestrongylus* is not expanding its range as rapidly.
- We isolated and sequenced Orf virus (a parapox virus) for the first time in muskoxen on Victoria Island from a case study in 2014, and have since confirmed orf infection in several muskoxen in 2015 and 2016.
- Based on serology, the bacterium *Erysipelothrix rhusiopathiae*, recently discovered on Banks and Victoria Islands, seems to have been present in muskox population since the 1970s and might be linked to population declines and mortality events.
- Genetic analyses indicate that populations from Banks and Victoria Islands are segregated from muskoxen on the mainland.

- There is extremely low genetic variability among muskoxen on Victoria Island, which may contribute to a lower resistance to diseases and decrease their ability to adapt to changing environments.
- We established a reliable method for extracting and quantifying cortisol in qiviut. Our results indicate that stress levels vary seasonally and yearly and declining muskox populations may be more stressed than others.
- We are using ecological models based on data and the Metabolic Theory of Ecology to help inform our understanding of disease ecology, emergence, range changes and impacts in muskoxen.
- Molecular tools can be used to identify the presence of pathogens indirectly from non-invasive samples (e.g., fecal pellets) and provide a means to monitor parasite range expansion.
- Obtaining muskox health data through active surveillance is essential to inform evidence based management and contributes to the protection of public health, including food security and safety.
- Involvement of local people in wildlife health monitoring and documenting TEK/LEK is essential to understand dynamics and health of wildlife species. This ensures a surveillance system that is relevant and adapted to the local context.

OBJECTIVES

1. Assess muskox health and vulnerabilities using scientific investigation and traditional and local knowledge TEK/LEK.
2. Understand risk factors associated with, and consequences of, recently emerged pathogens such as lungworms, *Erysipelothrix*, and Orf virus.
3. Develop and implement an integrative and responsive monitoring and surveillance program.

KNOWLEDGE MOBILIZATION

- Over 20 presentations at scientific conferences
- Two manuscripts submitted, see below for references
- Several meetings with wildlife management decision makers
- Hosting of the 1st International Muskox Health Ecology Symposium in Calgary
- Seven reports and presentations to Inuit communities
- One oral presentation at the Senator Patrick Burns Middle School, Calgary
- One 2-part series TV documentary on muskox health in the "Eye on the Arctic" documentary series (http://www.rcinet.ca/eye-on-the-arctic/2016/12/05/is-climate-change-making-the-muskoxen-sick-on-victoria-island/)
- Mentoring of five northern research partners

INTRODUCTION

Recent events have raised concern about the health status of free-ranging muskoxen (*Ovibos moschatus*) in the Canadian Arctic, particularly in the western Arctic Archipelago (Banks and Victoria Islands in the Northwest Territories and Nunavut) where population declines, multiple mortality events, and emergence of new diseases are occurring (Kutz et al, 2015; Leclerc, 2015; Davison et al, 2013; Tomaselli et al, 2016). The poor muskox health and population declines have important consequences for species conservation as well as for the food security and socio-economic welfare of Inuit communities (Gunn et al, 1991; Lent, 1999).

In 2015, we identified and documented new threats to muskox populations in the Canadian Arctic, notably the emergence of pathogens such as the zoonotic bacteria *Erysipelothrix rhusiopathiae*, the rapid range expansion of two protostrongylid lungworms, and the confirmation of cases of contagious ecthyma or orf (parapoxvirus). We also used a participatory approach to identify possible causes of muskox declines and to implement a surveillance system with the collaboration of local Inuit communities.

Our work so far has set the basis for a long-term monitoring of muskox health in northern Canada which is accepted and implemented locally. This approach simultaneously ensures that detailed ethnoecological and ethnoveterinary knowledge important for such systems is recorded together with scientific knowledge, and ensures that the surveillance system is relevant and applicable in the local context (Mariner and Paskin, 2000; Catley et al, 2012).

Our goals for 2016 were: 1) to continue and expand our monitoring and sample and TEK/LEK collection; 2) to analyze the samples collected to date in order to investigate different aspects of muskox vulnerabilities and resilience (i.e. pathogens, physiology, stress, genetics); 3) to begin to bring the generated knowledge together into predictive models of range expansion of pathogens and their subsequent impact on muskox populations.

This multi-faceted approach that integrates both scientific and local knowledge and engages multiple stakeholders will provide new insights into the threats to muskox health, the resilience of this species, and the socio-ecological context in which to interpret these findings.

ACTIVITIES

Timeframe and study area: This project began in spring 2015 and encompasses the Kitikmeot region, Nunavut, and Inuvialuit region, NWT. Additional sampling has been done elsewhere in the Arctic when further context has been required.

Objective 1. Assess muskox health and vulnerability using scientific investigation and local and TEK/LEK

Muskox Sampling: We continued our successful muskox sampling program with the Hunters and Trappers Organization and Outfitters in Ikaluktutiak (Cambridge Bay) and entered into new partnerships with the Hunters and Trappers organizations in Ulukhaktok and Kugluktuk (Figure 1). The community of Ulukhaktok engaged in collection of fecal samples for muskox lungworm studies and agreed to partner with us to formally collect TEK/LEK on muskox health and ecology in 2017.

Genetics: Muskox populations may be poorly equipped to deal with rapid changes in climate conditions, changing disease and pathogen dynamics, and increasing environmental stress (Van Coeverden, De Groot et al., 2004). To better understand muskox health and vulnerabilities, we are using a multipronged approach: 1) Using neutral genetic markers, we will determine the genetic variation and genetic structure of muskox populations. This will increase our understanding of migration and contact patterns between different populations. 2) To track the dispersal and abundance of two muskoxen lungworms, we are developing a species-specific quantitative PCR protocol that will allow us to simultaneously identify both species of lungworm thought to pose a threat to island muskox populations. 3) We are assembling a *de novo* muskox genome to identify unique genetic attributes that have allowed muskoxen to exploit the harsh Arctic environment. The genome will also allow us to perform population genomics to identify patterns of local adaptation in muskox populations in response to local and changing selective pressures. We are focusing on genetic variation associated with immune response to identify potential variants associated with pathogen resistance. This information will provide insight into the capacity of muskox populations to adapt to the warming climate.

Stress: Validation of cortisol quantification in muskox qiviut were completed. Qiviut samples from 173 muskoxen harvested between January 2013 and

August 2016 in seven different locations have now been analyzed, along with five qiviut samples collected from mortality cases in 2014. Experiments to establish washing methods and evaluate the reliability of liquid chromatography tandem mass spectrometry for quantification of corticosteroids in guard hair were completed. Additional samples from animals harvested between October 2016 and early 2017 near Ikaluktutiak, Ulukhaktok, and Kugluktuk have been collected but not yet analyzed. Fecal glucocorticoid metabolite quantification has also been done in samples collected from October 2015 onwards, in collaboration with the Reproductive Physiology Unit of the Toronto Zoo.

Traditional and Local Ecological Knowledge on Muskox Health: We documented TEK/LEK in Ikaluktutiak to understand: the traditional food system; traditional and local knowledge about muskox population dynamics, health and disease status over time; environmental changes that might be associated with muskox population decline; and logistic and practicality of hunter based sample collection from harvested muskoxen. We did individual semi-structured interviews and group interviews followed by multiple feedback sessions to validate the analyzed data with participants.

Key informants were selected through the Kitikmeot Inuit Association and the local Hunters and Trappers Organization (purposeful sampling), as well as by asking participants to identify other key informants to include in the study (snowball technique) (Green and Thorogood, 2014). Semi-structured interviews and participatory methods were used both in the individual and group interview settings. Interviews were audio-recorded and key information was systematically transcribed to provide the basis for further analysis. The transcripts were analyzed through thematic content analysis, using both deductive and inductive approaches to code themes.

Objective 2. Understand risk factors associated with, and consequences of, recently emerging diseases including lungworms, Erysipelothrix, and orf virus

Lungworm Ecology and Emergence: We aim at investigating the ecology and range expansion of two emerging muskox lungworms *Umingmakstrongylus pallikuukensis* and *Varestrongylus eleguneniensis* in the Canadian Arctic and then to construct species distribution models for both lungworm species and for their gastropod intermediate host and apply these to determine future lungworm distributions under climate changing scenarios. To achieve this, we conducted purposive and opportunistic fecal surveys of muskoxen and caribou on Victoria Island, in the Kitikmeot region, and the High Arctic Islands in collaboration with local hunters, regional biologists, outfitters. Moreover, we experimentally determined temperature dependent development rates of *V. eleguneniensis* and *U. pallikuukensis* in the slug species *Deroceras laeve* (the main intermediate host) to evaluate the potential of the lungworms to expand their range. Finally, the generated data were used along with satellite derived temperature data from global climate models to create degree day maps from the 1970s to present. Projections on the potential range of the muskox lungworms were simulated under different climate changing scenarios.

Ecological Models for Transmission Dynamics and Impacts of Parasites in Muskoxen: Ecological models can be used to identify critical data gaps, guide experimental design, synthesize diverse data to understand complex population and community dynamics, forecast dynamics into the future, assess the uncertainty in these forecasts, and aid the design of management strategies (Restif et al. 2012; Urban et al. 2016). Within this project, we harness these different powers using a variety of approaches that are aimed at (i) understanding the mechanisms that are responsible for the emergence, transmission and range expansion of muskox parasites, and (ii) developing general modelling tools that can easily be applied by researchers with less quantitative experience for determining likely climate change impacts and corresponding management strategies.

Erysipelothrix Ecology: In the last few years, the bacterium *E. rhusiopathiae* has emerged as an important cause of mortality in muskoxen in the

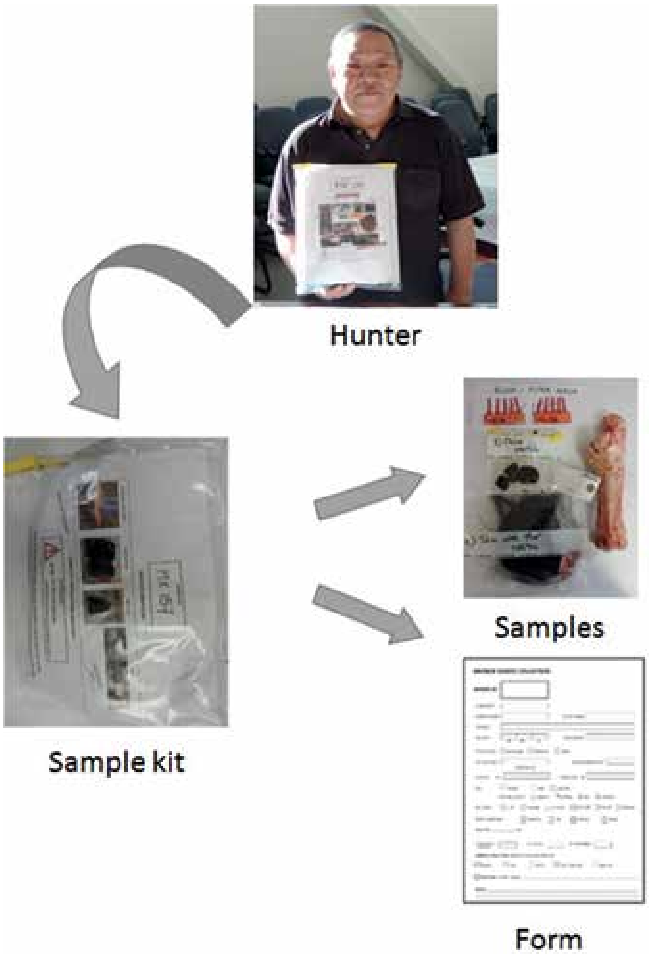

Figure 1. Hunter-based sample collection program: an Inuit hunter participating in sample collection from a harvested muskox using a specifically designed sample kit that includes collection of samples (such as blood on filter paper, feces, bone, fur) and recording animal-related information (e.g. location and time of collection, age, sex, pregnancy status, body condition status, any abnormalities).

Arctic, notably on Banks and Victoria Islands (Kutz et al., 2015, Forde et al., 2016). Our research seeks to understand the temporal and spatial patterns of *E. rhusiopathiae* exposure in muskoxen and its potential role in mortality events and population declines. To that end, we initiated a large-scale serological survey of muskoxen over the whole extent of the North American Arctic.

We used an ELISA test specifically developed and calibrated for muskoxen, to test 653 muskox sera, collected from six locations in Alaska and Canada from 1976-2015, for antibodies against the bacterium *E. rhusiopathiae.*

Orf Virus Detection and Ecology: In recent years, there has been a community-based observed increase in the occurrence of muskoxen with lesions on their noses, lips, and legs suggestive of orf infection. Orf is a parapoxvirus that commonly infects sheep and goats in many parts of the world; however, this infection is not commonly observed in muskoxen. Lesions from muskoxen on Victoria Island - one hunted muskox in 2014, seven muskoxen found dead in 2015, and numerous sport-hunted/commercial harvested animals from 2016 - were tested for orf virus. The lesions were present on the nose, lips, palate, legs, or nipples of muskoxen. Non-orf-like lesions and lesion-free screening samples were also tested for orf. Orf infection was confirmed using polymerase chain reaction (PCR) to target two different parapoxvirus genes in separate assays.

Other viruses, such as herpesviruses, which are commonly found in all mammals, can cause lesions on the skin and mucosal surfaces in immunocompromised hosts. All muskox samples were additionally screened for herpes virus infection to monitor for the presence of any previously uncharacterized virus. Herpesvirus screening was performed by targeting the viral DNA-dependent DNA polymerase (HVDPOL) gene using PCR with published primers by Vandevanter et al (1996). PCR-positive samples were sequenced by Sanger sequencing and analyzed through phylogenetic analysis.

RESULTS

Objective 1: Assess muskox health and vulnerability using scientific investigation and TEK/LEK

Muskox Sampling: Fifty sampling kits have been distributed in Ikaluktutiak and Ulukhaktok in 2016 and additional sampling kits will be shipped to those communities as well as Kugluktuk in 2017. Since the beginning of the project, 154 sampling kits have been returned by hunters and guides from Ikaluktutiak (n=132), Kugluktuk (n=17) and Ulukhaktok (n=5) and have been/are currently being analyzed.

In addition to community-based sampling, we also collected samples opportunistically or through collaboration with other groups. Those samples include: muskoxen found dead, euthanized or hunted in the presence of a member of our research team who was able to collect samples, and samples from research groups in Alaska and Greenland as part of international collaborations.

Genetics: Analyses were run on ~600 muskox samples and showed a low genetic variation across all samples tested to date with a high of seven alleles at OM54-23 and an average of 4.3 alleles (Table 1). Structure analyses on the samples genotyped identified two clusters. The muskox populations divided between the islands (Victoria Island and Banks Island) and the mainland populations (Figure 2).

The lungworm detection assay has been optimized for fecal extractions. 120 individuals from Victoria Island have been tested. 61 individuals were determined to have been infected by both lungworm species (*U. pallikuukensis* and *V. eleguneniensis*), five were infected by only *U. pallikuukensis* and 54 were found to have no infection. However, results obtained through detection of lungworm DNA agreed poorly with results from coprological analyses.

Regarding genome sequencing, next generation sequencing runs produced ~1.3 billion paired reads. After cleaning the reads for contaminating primer/adapters, duplicates and low quality reads, ~800 million paired reads remained, resulting in approximately 80X coverage (i.e. each nucleotide in the genome is sequenced 80 times.)

Stress: 150 qiviut samples were collected from adult muskoxen near the communities of Sachs Harbour, Ulukhaktok, Paulatuk, Kugluktuk and Ikaluktutiak, and on the Kent Peninsula and Lady Franklin Point. We found a significant seasonal pattern, with qiviut cortisol higher in the fall and winter than in the summer (Figure 3). Differences between sexes and years were also highlighted, with qiviut cortisol levels increasing from 2013 to 2015 (Figure 4), and higher in males than in females. There were also some differences between populations with samples submitted from Ikaluktutiak having the highest cortisol levels. A manuscript of these results ('Qiviut cortisol quantification in muskoxen using liquid chromatography coupled to tandem-mass spectrometry') will be submitted in spring 2017.

Traditional and Local Ecological Knowledge on Muskox Health: Four major themes emerged from participants' narratives when exploring the importance of muskoxen both at the individual and community level and summarized as nutritional, socio-cultural, economic, and environmental importance (Figure 5). Additional subthemes arose from a deeper analysis of each domain, providing a richer description of participants' values and attitudes toward muskoxen (Figure 6). Within the nutritional domain, we

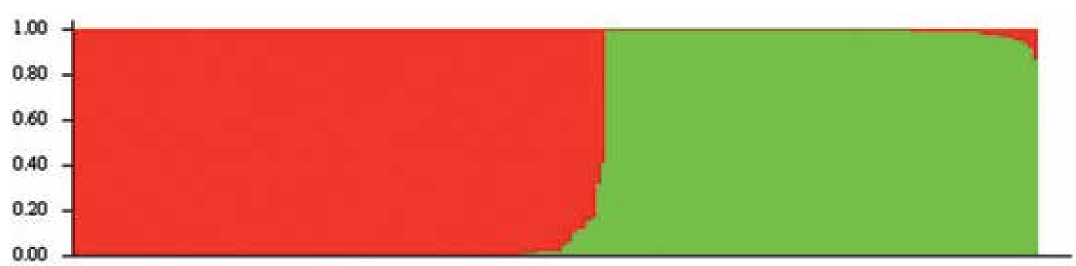

Figure 2. Bar Plot of visual output of structure data. Two inferred clusters represented by red and green coloring.

explored the relative importance of muskoxen among participants. An Inuit hunter said "…the importance of muskox [as a source of food] fluctuates along with the abundance of caribou. When caribou are plenty we don't rely on muskox, [but] we tend to get more muskox when the caribou are not plentiful". This quote effectively summarizes the country food relationship among caribou and muskoxen, the latter being more represented in the diet when caribou are less locally accessible and available. Finally, local decline of muskoxen was perceived to have significant and multiple impacts on the local economy, food security, as well as socio-cultural dimensions. An adult Inuit said "I have learned from elders that muskox are important and I am the next [generation] after the elders…It is important that younger generations try to keep the tradition, but muskox herds are dwindling". This quote strongly emphasizes how the presence of muskoxen contribute to foster intergenerational connection between elders and younger Inuit. Ultimately, this component of the research further justifies the importance of implementing a surveillance system to monitor muskox population health and trends.

Table 1. Summary of genetic variation within 11 neutral microsatellite loci tested. Consists of the number of alleles found at each locus, the observed heterozygosity and the expected heterozygosity.

Locus	Number of alleles	HObs	HExp
MoDIAS 1	6	0.203	0.419
OM58-06	4	0.043	0.489
OM51-19	6	0.336	0.489
OM56-27	2	0.009	0.009
OM54-23	7	0.253	0.685
OM53-38	5	0.467	0.638
OM53-12	6	0.391	0.686
OM55-04	5	0.328	0.508
OM50-8	4	0.264	0.315
MoDIAS 3	2	0.096	0.436
OM51-16	5	0.309	0.652

Objective 2: Understand risk factors associated with, and consequences of, recently emerging diseases induced by lungworms, Erysipelothrix, and orf virus

Ecological Models for Transmission Dynamics and Impacts of Parasites in Muskoxen: As a first step, we developed a general modelling framework that can outline likely changes to the transmission dynamics and impacts of parasites on hosts under climate change. To facilitate its use in research groups with different foci and backgrounds, and thus maximize

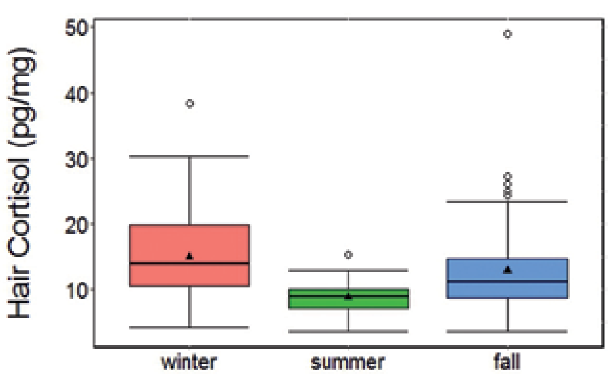

Figure 3. Seasonal patterns of qiviut cortisol (pg/mg) in adult muskoxen (n=150).

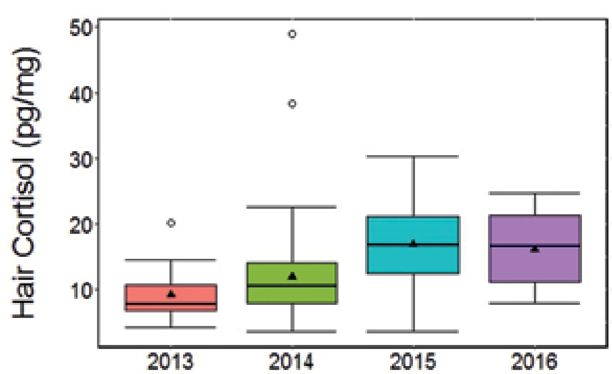

Figure 4. Yearly patterns of qiviut cortisol (pg/mg) in adult muskoxen (n=150).

Figure 5. Word cloud representing the words that were said by participants when talking about the importance of muskoxen, which is summarized in 4 major domains defined as nutritional, economic, socio-cultural, and environmental importance.

Figure 6. Visual representation of the themes (darker green) and subthemes (lighter green) that emerged from the analyses of the participants' narratives.

data quality and comparability, we provided a step-by-step guide on both model development and on how to design experiments that will provide unbiased estimates of the temperature-dependency of disease transmission (Molnar et al., submitted). PhD student Alexander Nascou is using these new approaches to synthesize lab and field data from Dr. Kutz's lab into temperature-dependent dynamic models of muskox parasite transmission. Initial analyses have focused on estimating the temperature-dependency of development and mortality rates of the free-living parasite stages and the stages within intermediate snail hosts (Figure 7).

Lungworm Ecology and Emergence: *Fecal surveys*: Results from fecal samples analyzed in 2015/2016 further support that there has been substantial range expansion of *U. pallikuukensis* and *V. eleguneniensis* to the higher latitudes. *Umingmakstrongylus pallikuukensis* has expanded its range more rapidly and covers a broader geographical range than *V. eleguneniensis* (Figure 8). We detected latitudinal gradient in abundance of both lungworms (Figure 8). Lungworms were also found in sympatric caribou fecal samples but in lower abundance.

Parasite ecology: Results from temperature dependent development trials at five different temperatures from 8 to 24 °C suggest that *V. eleguneniensis* has a higher development threshold and requires more degree days of heating than *U. pallikuukensis* to develop to the infective stage. Freeze tolerance experiments suggest that those parasites are extremely tolerant to freezing. There was no significant difference in freezing survival between the two lungworm species ($P > 0.05$). More than 80% of larvae can survive long term freezing (over six months) in temperatures as low as -80°C.

Modeling distribution: Preliminary degree-day modeling for *U. pallikuukensis* suggests that historically, temperatures on Victoria Island were unsuitable to support an annual life cycle but that recent warming has made most of the regions of Victoria Island suitable. Similarly, preliminary results suggest the differential range expansion of these parasites, as observed in our data (Figure 8), and future maps suggest that *U. pallikuukensis* will continue to expand at a greater rate than *V. eleguneniensis* (Figure 9).

Erysipelothrix Ecology: We have detected antibodies reacting with *Erysipelothrix* in muskox in archived samples dating back to the 1970s. Temporal patterns in seropositivity to *Erysipelothrix* varied between regions (Figures 10 and 11). In Alaska, we documented an endemic situation with a seroprevalence around 20-40% in most of the years in all investigated populations. The situation in Canada seems different with the prevalence on Banks Island alternating between years at 40% and years with much lower seroprevalence. This pattern could be consistent with episodic outbreaks, possibly linked to reservoir hosts or ecological conditions.

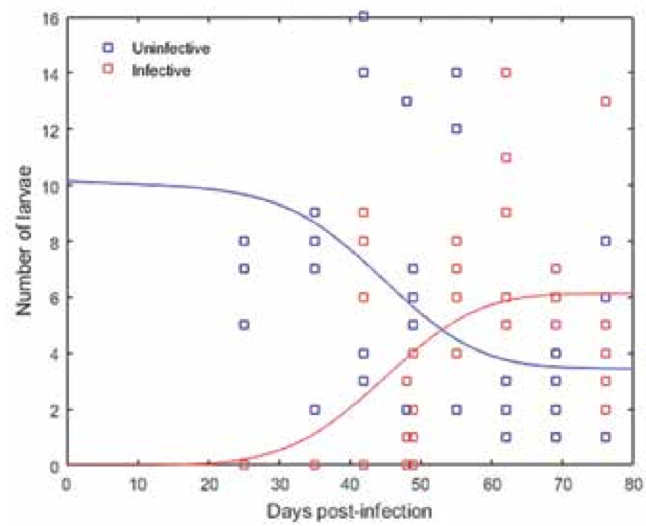

Figure 7. Development of Umingmakstrongylus pallikuukensis within their intermediate snail host from the L1 stage (uninfective to muskoxen) to the L3 stage (infective to muskoxen) for the example of 11.5°C. Data are the numbers of infective and uninfective larvae in different snails (sampling is destructive so each snail was only examined once) as a function of time since infection with L1 larvae. Maximum likelihood fits of the model to the data (solid lines) provide estimates of both mortality and development rates.

<u>Orf Virus Identification Ecology</u>: We have successfully sequenced the orf B2L gene of one muskox from 2014, seven from 2015, and so far, three animals from 2016. As expected, all animals presented to sample collection with clinical orf-like lesions have also been PCR-positive for orf infection. Our sequences were aligned and a phylogenetic tree was constructed to demonstrate the relationship of orf strains with known strains (Figure 12). Orf B2L sequences from this study are highly similar and show no variation thus far.

Sequences of the orf DPOL gene, as well as the herpesvirus HVDPOL gene have been determined for the animals from 2014 and 2015, but not yet for 2016 (data not shown). These viral gene sequences also indicate high degrees of similarity between the strains infecting muskoxen of Victoria Island, Nunavut. Yet, the only herpesvirus detected in these muskoxen is *Ruminant rhadinovirus* type 1, as expected. This infection will be further characterized.

DISCUSSION

The combination of community-based TEK/LEK collection and classical western scientific methods for the research conducted by our group in 2016 has yielded important results regarding genetic, parasitological and ecological knowledge of muskox populations and epidemiological knowledge of relevant pathogens.

Our community-based muskox sampling program was refined and expanded to new communities. Samples from each animal are distributed among each of our projects providing a comprehensive assessment of the health of each individual (e.g. genetic, stress, infectious disease, body condition) and TEK/LEK inputs from hunters and community members are incorporated into these analyses.

Our work on muskox genetics so far has demonstrated an extremely low amount of variation. Our results also indicate that islands and mainland muskox populations tend to be segregated with little contact between them. We further developed our lungworm detection assay but found a poor agreement with results from coprological analyses (i.e. Baermann funnel method). This is suspected to be due to pellet variability so a subsample of pellets used for DNA extraction will also be physically extracted

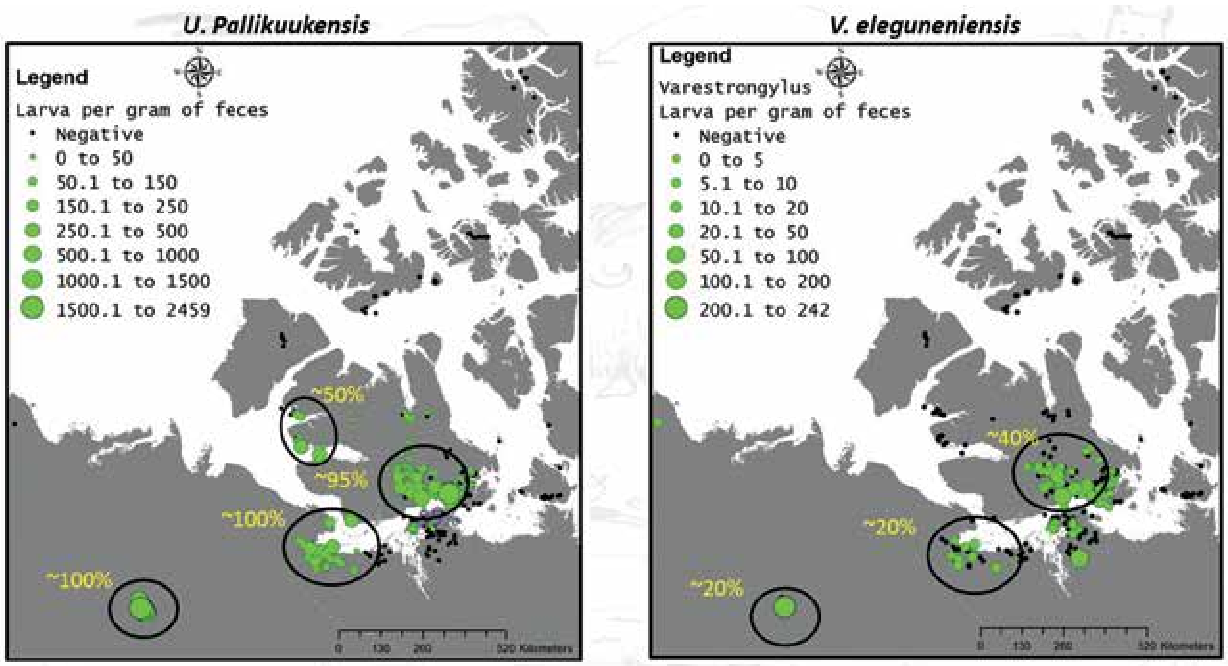

Figure 8. Distribution of the two lungworms based on fecal samples collected in 2013-2016. The size of bright green circles indicates the intensity of infection. The black circles indicate the sites tested negative for lungworms.

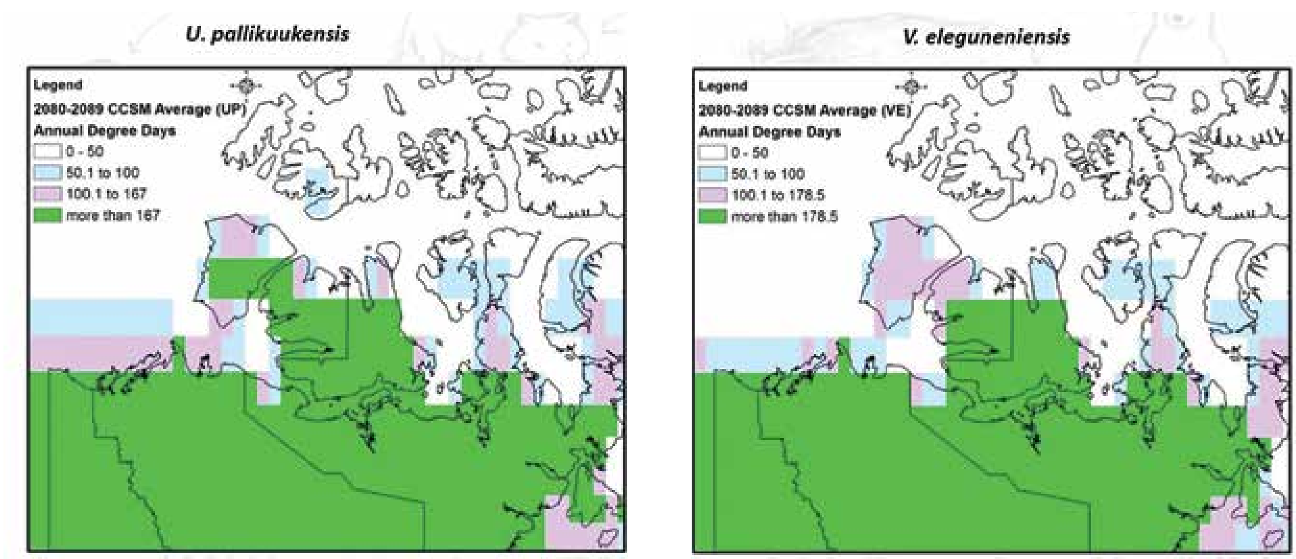

Figure 9. Future habitat suitability maps for the two lungworms based on annual accumulated degree-days. The green zone represents the area suitable for the completion of the life cycle in a single year. The simulations were run using global climate model CCSM4 in highest emisssion scenario (RCP 8.5) for the decade of 2080.

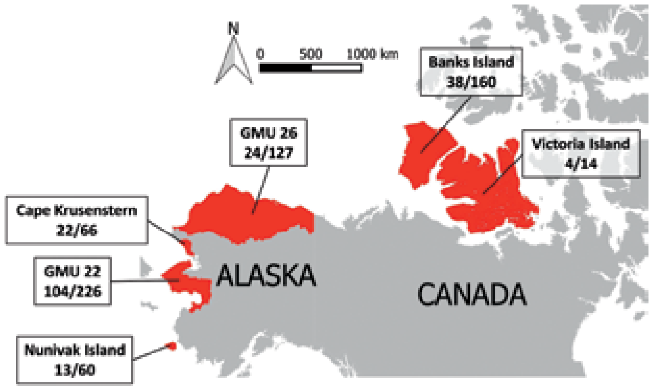

Figure 10. Origin of 653 muskoxen tested for antibodies against E. rhusiopathiae in Alaska, Canada, and Greenland. For each region, the number of positive samples over the total number of samples are shown. GMU = game management unit.

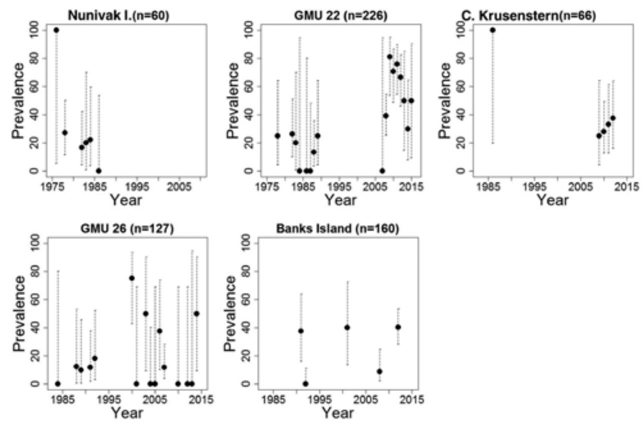

Figure 11. Sample seroprevalence for E. rhusiopathiae in 653 muskoxen from five different regions and game management units (GMU) in Alaska (Nunivak Island, GMU22, Cape Krusenstern, GMU 26) and Canada (Banks Island). Black dots represent sample prevalences for each year in percent. Dotted lines are binomial confidence intervals.

to assess the validity of the assay. In addition, we are also investigating genetic structure of the lungworm populations to evaluate contact and migration patterns of their muskox host. However, to date, the samples tested for lungworms using the assay have been from Victoria Island, so more samples must be run from Banks Island and mainland populations to compare to neutral genetic results and population structure. A manuscript on neutral genetics in context with disease/lungworm dispersal is currently in progress.

Some of the largest endemic muskox populations are undergoing rapid population declines and these declines may be in a large part attributed to interactions among climate change and pathogens. Whether muskoxen will have the capacity to adapt to the changes they are facing in their environments is unclear. We anticipate our research in muskox genetics will fill in many gaps surrounding muskox exposure to selective pressures, and their sensitivity to change and adaptations.

Stress can lead to increased vulnerability to infectious disease and other threats. Our goal is to evaluate the use of hair stress hormones as a method that can be incorporated into health surveillance protocols as an indicator of health. Our methods demonstrate reliable quantification of cortisol from qiviut, and we provide the first data on hair cortisol in muskoxen. These results suggest slight differences between populations with different trajectories and demonstrate significantly higher qiviut cortisol levels in the fall and winter than in the summer, as well as significant differences between years and sexes. This highlights the importance of controlling for sex, season and year when analyzing stress levels. Next, we will use existing hunter-based samples and data together with new comprehensive scientific sampling to evaluate the relationship between qiviut cortisol as well as fecal glucocorticoid metabolite levels and other indicators of fitness in individual animals and populations. An experimental study will concurrently be carried out using captive muskoxen. This will enable us to establish the patterns of cortisol incorporation in qiviut and give us solid foundations to accurately interpret our results in wild muskoxen.

Observations made by TEK/LEK holders of a major decline in muskoxen around Ikaluktutiak, together with observations of an overall deterioration of health status of the animals, measured as poorer body

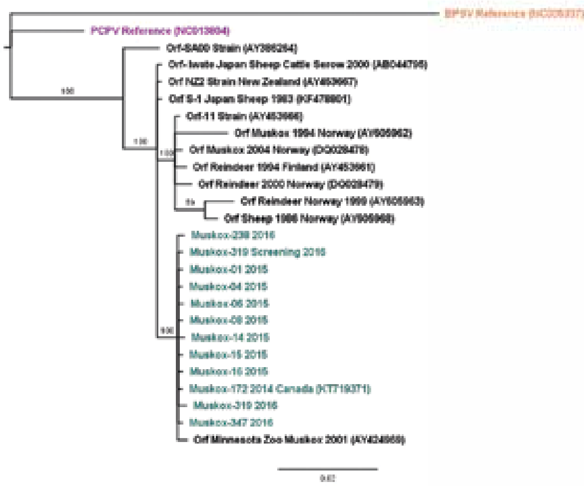

Figure 12. Bayesian phylogeny of the B2L gene from orf virus strains. Sequences from this study are shown in blue and demonstrate very little variation. Our strains group together in one clade with a previously identified orf strain from an infected North American muskox in the Minnesota Zoo in 2001. Bovine papular stomatitis virus (BPSV) shown in orange and Pseudocowpoxvirus (PCPV) in purple are other genera in the family Parapoxviridae. Branch numbers represent confidence as a probability percentage, and the scale bar indicates nucleotide substitutions per site. Bayesian analysis was performed with a burn-in value of 1,000.

condition, increased observation of diseases, and die-off events suggest an increase vulnerability of local muskoxen. Particularly, the observations of decline in the juvenile age class suggest poorer reproduction of muskoxen, which might be a consequence of poor nutritional status, or may be linked to infectious diseases affecting conception, maternal health, or increased mortality of the young. Participants' description of muskox "acute mortality events" has led to improved characterization and quantification of muskox die-offs that had been under-reported in the area, and increased our knowledge about seasonal patterns of muskox disease outbreaks. Engagement of community members in the interview process was, and continues to be, exceptional, as was the quantity and quality of the data collected. Results were presented at the muskox management workshop and incorporated into management plans. In addition, researchers and community members conjointly presented the validated data during the Annual ArcticNet Scientific Meeting (Winnipeg 2016).

Our more recent results demonstrate that the parasites *U. pallikuukensis* and *V. eleguneniensis* have expanded at differential rates on Victoria Island. Although Banks Island and more northern arctic island populations are still free of those parasites, ecological modeling indicates that both species of lungworms are likely to further expand their range to the north in the future.

Analyses of data on the temperature-dependency of parasite transmission and reproduction will be completed in spring 2017, and then synthesized along with all other parameters into models that outline whether the parasite could establish and persist in an area, given prevailing temperature patterns and trends. As a second step, we will explore the interplay and respective importance of these temperature dynamics and host movement in determining parasite ranges and range changes, using a new theoretical framework (Peacock et al., submitted) that was specifically developed for this purpose. This framework reveals intricate interactions, for example, between host movement speeds and parasite development rates that determine whether or not the parasite can keep up with its climatic niche.

Our findings confirm that, although *E. rhusiopathiae* was first detected in 2012 in muskoxen in Canada, it has been circulating in muskoxen in both Canada and Alaska since the 1970s. In two instances, the rise in seroprevalence coincided with abnormal mortality rates and the isolation of *E. rhusiopathiae* from dead animals during the same time period, suggesting a possible causative role for *Erysipelothrix*.

Further sampling of muskoxen from Victoria Island and the Canadian mainland is currently ongoing and will help paint a more complete picture of the situation regarding exposure to *E. rhusiopathiae* in muskoxen populations. In addition, we are currently testing more than 1,000 caribou sera for antibodies against *E. rhusiopathiae* and testing snow goose cloaca swabs for the bacteria. Those results will inform further on the ecology of the disease and help to understand potential epidemiological links between the different sympatric species of the Arctic.

Using molecular techniques, we have shown that orf virus is present in several muskoxen from Victoria Island, Nunavut. It is unusual for orf to be found in adult animals, and the presence in muskoxen suggests that these animals may be immunologically compromised. Additionally, the high degree of sequence similarity suggests that a single strain of previously uncharacterized orf virus is infecting muskoxen from 2014, 2015, and 2016. Our preliminary findings of *Ruminant rhadinovirus* type 1 herpesvirus in these tissues is expected, but this infection may play an additional role in causing morbidity in immunocompromised muskoxen as this group of viruses are often activated by stress. Further characterization of these viruses in discovered dead, sport-hunted, and commercially harvested muskoxen is needed.

CONCLUSION

This body of works constitutes a multi-agency and multidisciplinary approach to understanding the health and resilience of muskoxen in a changing Arctic. By taking a holistic approach to evaluating health and integrating multiple disciplines and sources of knowledge (scientific, local, and traditional) we have made substantial advances in our understanding of the current status of muskox health, ranging from body condition to infectious disease and genetics. We are delving into the ecology, transmission, and impacts of pathogens using a combination of field, laboratory, and modeling studies. We are also testing potential indicators of health (e.g., stress), and developing a health surveillance framework that uses multifaceted approaches with LEK, TEK, Arctic BioMap, and community, government, and scientific sampling.

This research is necessary to understand what effect changing environments will have on wildlife health and sustainability, food safety and security, and health of northern communities. Additionally, through this research, we will establish programs for ongoing health surveillance and begin to develop strategies to mitigate the negative impacts the changing arctic environment has on muskox populations.

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WATER SECURITY AND QUALITY IN A CHANGING ARCTIC

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ABSTRACT

Water is a crucial component of ecosystems and plays a vital role, in conjunction with climate and permafrost, in the stability of arctic landscapes and ecosystems. The security of water for ecosystem services, community use and economic development depends on knowledge by northerners regarding the impact of climate and permafrost change on water and the interactions these changes have with other terrestrial components like vegetation and animals. Projected climate changes are anticipated to substantially affect winter snowpack and melt season conditions that will in turn affect hydrological response, water quality, as well as permafrost and landscape stability. These changes will affect related watershed processes such as nutrient and contaminant cycling and fluxes, erosion, primary production of tundra vegetation and greenhouse gas exchange with the atmosphere. However, there is considerable scientific uncertainty with regards to many of these components, and few comprehensive datasets to assess the potential impacts of climate changes on water resources in the Arctic. Moreover, there is a compelling need to support and develop capacity in northern communities to direct and participate in relevant research, and to link knowledge generated by different research communities.

This project seeks to address these gaps by pursing both state of the art, integrated watershed research, and to build capacity in communities to undertaken long term, sustainable watershed research in the Arctic. The project will carry out research at the Cape Bounty Arctic Watershed Observatory (CBAWO) on Melville Island near the Nunavut/NWT border. With support from ArcticNet since 2005, research at CBAWO has focused on an integrated approach to identify the key processes that link watershed and landscape processes and to model their vulnerability and response to climate change. This location is the only comprehensive watershed monitoring observatory in the Canadian Arctic Archipelago and provides key insights into landscape and watershed processes in the western islands. With support and collaboration with numerous community stakeholders, we have expanded this watershed approach to the Apex River near Iqaluit. Since 2013, this project has undertaken to build local research capacity, engage stakeholders, and attract research interest to a watershed with significant community interest. This project seeks to substantially expand the Apex River research as a means of transferring knowledge gained at CBAWO, while also advancing our fundamental knowledge of water and terrestrial change in both locations. The multidisciplinary research team has diverse expertise that has allowed them to develop an integrated approach to resolving uncertainties in the response of Arctic watersheds to climate change.

KEY MESSAGES

Cape Bounty

- Modelling demonstrates key areas on the landscape that are most susceptible to permafrost disturbance.These models can be used regionally with good results.
- Sediment erosion and transport appears to have substantially recovered from permafrost disturbance in 2007 indicating that at the catchment scale, recovery occurs in less than a decade.
- Subsurface water flows are an important contributor to river baseflow and appear to be highly efficient, similar to temperate regions.
- In the late summer subsurface flow is a contributor to runoff generation and appears to follow preferential pathways.
- Catchment variations in surface water chemistry and nutrients appear to be highly localized.
- The lakes at CBAWO continue to show a strong hydrochemical response to permafrost change in the catchments.This change is also reflected in the

otoliths of arctic char and in diatom communities in the East Lake, while slumping (and resulting turbidity) in the West Lake obscures these impacts.

- Concentrations of mercury in landlocked arctic char were significantly greater in West Lake, which is impacted by permafrost disturbances and subaqueous slumps of sediment, compared to unimpacted East Lake.
- Mercury concentrations in landlocked char have declined significantly in East Lake but are increasing in West Lake over the period 2008-2016.
- Concentrations of fluorinated chemicals are detectable in char as well as in water but unlike mercury are similar in both lakes.
- Dissolved organic matter (DOM) differs between rivers and ponds in ^{14}C, DOC age and compositional characteristics in the West River catchment.
- The composition of dissolved organic matter from subsurface water sources, resembles composition of DOM in late season rainfall runoff.
- Seven years of experimental warming and enhanced snowfall showed that warming alone led to a significant increase in carbon dioxide removal from the atmosphere and storage in the plants and soils in the tundra ecosystem.
- Average concentrations of pCO_2 and pCH_4 in West Lake were lower than in East Lake, but all concentrations were above atmospheric equilibrium, suggesting that these two lakes are sources of these two greenhouse gases to the atmosphere.

Apex River

- NRI provided broad ranging logistics support, supervision, and coordination for 2016 research activities in the Apex Watershed as part of the ArcticNet project Water Security and Quality in a Changing Arctic. Collaboration and local capacity for water research continues to expand through this project.
- Field work in 2016 has greatly advanced our understanding of the physical factors controlling the storage and routing of shallow groundwater within the Apex River watershed.
- We made excellent progress towards further development and refinement of a methodological protocol for annual snow surveys within the Apex River watershed, with the goal to establish a practical and statistically representative long-term snow monitoring program. This work is being conducted in close collaboration with Nunavut Research Institute and Nunavut Arctic College Environmental Technology Program (NAC ETP). NAC ETP students and instructors are helping with field logistics and sampling and we are working towards development of a snow hydrology curriculum for the program.
- Queens Analytical Services Unit (ASU) operates laboratories at Queens University, Kingston as well as a seasonal laboratory at the Nunavut Research Institute, Iqaluit. Samples were collected and analyzed for a variety of parameters including metals, as well as nutrients and other dissolved indicators.Some of the testing was carried out in Iqaluit, close to the collection point of the water samples and the rest of the testing took place at ASU, Queens University.
- In a separate but related project "Environmental Sampling and Analysis Training", carried out by the ASU at the Nunavut Research Institute (NRI), training and support for Inuit students and ArcticNet researchers was provided, increasing local capacity for water research.

OBJECTIVES

Water is crucial for a wide range of northern stakeholders, including: individuals, communities, government and industry. Water also plays a vital role, in conjunction with climate and permafrost, in the stability of arctic landscapes and ecosystem integrity. Projected climatic changes are likely to have widespread impacts on permafrost stability, hydrology, and terrestrial ecosystem function, which combined will significantly impact watershed biogeochemistry and water quality (e.g. contaminants, sediments, microbial activity, organic matter and nutrient content).

Hence, our overall project goal is to enhance knowledge regarding water security in the Canadian Arctic through a dynamic integrated collaborative research program. Our first objective is to apply an innovative and leading edge integrated watershed approach to identify how climate change and permafrost stability drive freshwater quality and availability in arctic watersheds. This comprehensive research program, based on deep collaborative efforts developed over the past decade, is focused on understanding how i) changing water pathways (e.g. subsurface flow); ii) changing water sources (e.g. ground ice melt, and summer rainfall); and iii) thermal perturbations and physical disturbance of the permafrost and surface ecosystem (vegetation, soil) impact the seasonality and quantity of surface water volume and key water quality indicators (nutrient, sediment, organic matter, microbial, and contaminant) in arctic watersheds.

Our second major objective is to transfer this research knowledge and experience to build sustainable research capacity with northern stakeholders through a (2013+) collaborative research program in the Apex River watershed near Iqaluit, NU. Research at the Apex River is motivated by interest and concerns about changes to river flow and water quality by local decision makers, particularly the City of Iqaluit and residents, and has developed into the only sustained research program associated with this important water source.

Additionally, the project aims to provide training and support for Inuit students and ArcticNet researchers as part of a synergic education/analysis initiative. The business of sample collection, storage and especially the analysis of environmental contaminants can be complex, yet it lends itself perfectly to production of HQP. The training of indigenous populations will ensure a 'brain gain', which most likely will remain in the North. Being part of projects where the local population can decide the best sampling locations for specific projects, do the analysis and see the results is a key objective.

In 2016, our objectives were:

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- Evaluate the hydrological processes related to climate and permafrost change to determine runoff and quality sensitivity.
- Identify the impacts of deep summer thaw and surface disturbance on sediment transport and dissolved nutrient and carbon fluxes.
- Better understand the landscape and seasonal controls on the composition and role of dissolved organic matter (DOM) chemistry in biogeochemical cycling.
- Identify the physiochemical changes in downstream lakes in response to watershed changes.
- Continue to determine mercury and trace elements in landlocked Arctic char to develop a time series from which impacts of permafrost disturbances in the catchment of West Lake can be assessed.
- Determine if East and West Lakes are sources or sinks of CO_2 and CH_4 to the atmosphere, and if there are zones of CO_2 and CH_4 production in these lakes.
- Continue to determine tributary inputs of mercury and methyl mercury to West and East Lake at Cape Bounty as part of an assessment of mercury biogeochemistry at Cape Bounty.
- Investigate levels and trends of persistent organic pollutants (POPs) in char and in waters of East and West Lake and tributaries.

- Develop efficient methods for estimating vegetation coverage and examine changes across a latitudinal gradient (and over time) in the Canadian Arctic.
- Determine controls over landscape stability for developing landscape-scale permafrost susceptibility models.
- Quantify the impact of enhanced temperature and snowfall on plant phenology and exchange of greenhouse gases between the land and the atmosphere.

Apex River

- Provide overall support, coordination, and guidance for field and lab based research in the Apex river watershed as part of the Arctic Net project Water Security and Quality in a Changing Arctic.
- Provide training and analytical expertise/quality control for the analysis of collected water samples in a CALA accredited analytical testing laboratory.
- Develop better models of snow redistribution and end of season snow accumulation in the Apex River watershed to support hydrologic forecasting with physically-based hydrologic modelling.
- Develop knowledge and tools that can be used to predict the rates and patterns of groundwater discharge to surfaces waters, to understand the response of arctic freshwater ecosystems to environmental change.
- Better understand the role of DOM chemistry in biogeochemical cycling, DOM age and composition in river and pond samples.

KNOWLEDGE MOBILIZATION

Cape Bounty

Key research results were presented at the ArcticNet Annual Scientific meeting by team researchers and students (Lafrenière, Fouché, Gillman, Rudy, Arruda, Scott, Fransen, Pouliot, Chiasson-Poirer), which included a significant number of northern stakeholders. General results and photographs were (and continue to be) communicated to northerners using the CBAWO blog site (CBAWO.blogspot.ca), and through our Facebook page (www.facebook.com/CBAWO).The latter appears to be an excellent way to communicate information to Resolute residents due to a high level of activity on a daily basis. As with past seasons, a Resolute resident worked with us in the field and we unsuccessfully sought to bring a student to the camp in 2016. We will continue with our efforts to increase direct community involvement to share knowledge and offer training and experience.

All researchers present results at scientific meetings, including international conferences, including the American Geophysical Union (e.g., invited talk Lafrenière et al.). We also contribute to working groups in Canada on focused topics (groundwater in permafrost, thermokarst). Results for mercury and organic contaminants in char and in lake and river waters will be presented as posters at the Northern Contaminants Program results workshop planned for Iqaluit in Sept. 2017, which will be attended by representatives from many communities in Nunavut. The biogeochemistry work at Cape Bounty will also be communicated in the upcoming PCSP Science Report for 2016.

Apex River

The Canada-Nunavut Geoscience Office (CNGO) is a key institution providing geoscience information to develop better infrastructure, resources management and geoscience knowledge for Nunavut communities. To achieve our objectives we intensified our collaboration with the CNGO during the 2016 field season. To rapidly communicate our approach and preliminary findings from 2016 we submitted a paper that was published in the CNGO Summary of Activities 2016, a journal managed by the CNGO and available for free to the public. Additionally, while in Iqaluit we organized a webinar of the Association for Polar Early Career Scientists

(APECS) in collaboration with Jamal Shirley, manager of research design of the Nunavut Research Institute, to share our methodology and preliminary findings with other researchers from Nunavut and Europe. Preliminary results were also presented at the ASM.

M. Richardson participated as a volunteer instructor on the NAC ETP spring field course at Crazy Lake in April 2016 and conducted snow hydrology activities with ETP students, including ski-doo based surveys throughout the Crazy Lake watershed. Carleton MSc student Keegan Smith worked extensively with more than 10 individual NAC ETP students during spring 2016 and benefitted from their enthusiasm and knowledge working as field assistants. In return, these students received hands-on training in snow hydrology and micrometeorological techniques.

Training and knowledge transfer has always been one of the key mandates of the ASU. In recent years, we have been involved with training at the Nunavut Research Institute (NRI) in Iqaluit and have established the 'Iqaluit Analytical Services Unit' with the support of Mary Ellen Thomas, Senior Research Officer and involvement/cooperation of Jamal Shirley, Manager, Research Design and Policy Development.

ASU is accredited by CALA (formerly CAEAL) to the standards of ISO/IEC 17025 and are an environmental analytical laboratory. Dissemination of the knowledge and experience gathered whilst working on a wide variety of environmental projects is a key part of what the unit does – working with undergraduates and graduate students, professors, industry, local and global businesses. We take a practical and applied approach to many of our analytical projects including 'remote site' operations. In the past we have established and operated mobile laboratories in Resolution Island, Nunavut; Cape-Dyer, Nunavut; Winisk, Polar Bear Provincial Park, Northern Ontario and Tundra Mine, Northwest Territories (amongst others).

Cape Bounty

ACTIVITIES

In 2016, we carried out a comprehensive hydrological field program focused on water pathways and flow generation, sediment transport, and hydrochemical variability across the two main watersheds at Cape Bounty. Work included: meteorological monitoring at two stations; soil monitoring at eight stations; soil monitoring and pore water sampling in the ITEX plots; end of winter snow survey; seasonal discharge and water sampling at eight stations; soil water flow studies in headwater and slope-channel settings; and spatial sampling of sediment and water quality measures across both the West and East River. Additionally, the two downstream lakes were also monitored and sampled to complete the "source to sink" approach of tracking climate and permafrost changes on surface water systems. This comprehensive watershed program involved two PDF, one PhD, five MSc and one BScH student working in the field and on data analysis. This work was carried out from mid-May until mid-August and represented our most intensive hydrological monitoring effort to date (and arguably, ever carried out in the Canadian High Arctic).

A second hydrological focus of the 2016 field season was to investigate the seasonal controls over the abundance, optical characteristics (absorbance and fluorescence), and lability (biodegradability) of dissolved organic matter (DOM). In order to examine this question we collected replicate samples from soils from across different vegetation classes and disturbed areas, and (ii) in ephemeral ponds or seeps (e.g. soil pipes) that are fed by subsurface water bodies on three separate occasions over the course of the summer of 2016. Recent findings from previous work at CBAWO suggest that fresher and more labile DOM is exported during periods of deep thaw and from areas subject to disturbances (Fouché et al. in press). Since the absorbance and fluorescence characteristics of DOM indicate the structural characteristic of the DOM, these are widely used as proxies for the relative lability (biodegradability) of DOM in soils and runoff. However, recent studies demonstrate that that several other factors in addition to the structural character of the DOM, including for example nutrient concentrations, have important controls on the lability of DOM (e.g. Marin-Spinotta, 2014). The aim of this study is therefore to use a series of laboratory incubation experiments to determine if changes in the structural properties of the DOM (as determined by optical characteristics) at CBAWO are in fact related to the rates of decomposition of DOM.

Additionally, detailed organic matter analysis was undertaken to examine the chemical difference between river and pond waters from 14 river and six pond sites that were collected in summer 2014 and 2015 from the West River catchment. The concentrations of dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) were quantified and one- and two- dimensional (1-D and 2-D) analyses were conducted using a Bruker BioSpin Avance III 500-MHz NMR spectrometer (Mitchell et al., 2013). The 1H NMR spectra were integrated into four regions: 1) materials derived from linear terpenoids; 2) carboxyl-rich alicyclic molecules; 3) carbohydrates and peptides; and 4) aromatic and phenolic components (Woods et al., 2011). Ultraviolet-visible absorbance and fluorescence emission excitation matrices of the thawed and filtered samples were collected at room temperature using a Horiba Aqualog spectrometer as described in Fouché et al. (in press). The optical indices including specific ultraviolet absorbance (SUVA), E2/E3 ratio, fluorescence index (FI), biological index (BIX), and humification index (HIX) were calculated (Fellman et al. 2010). The fluorescent DOM components were fractionated using the parallel factor analysis (PARAFAC) as described in Murphy et al. (2013). In addition, sample radiocarbon analyses were conducted.

Other activities related to understanding the landscape and seasonal controls on the composition of DOM, included investigating the impacts of warming and snow accumulation on the composition and pool of nutrients and DOM in soils. To investigate these controls on DOM, in 2016 we collected soil pore waters from three of the International Tundra Experiment (ITEX) sites, where we use open-top chambers to warm soils, and snow fences to accumulate snow.

Research in 2016/17 also focused on completing an assessment of the impact of seven years of enhanced warming and enhanced snowfall on plant phenology and carbon exchange between the land and the atmosphere. This experiment, done in collaboration with Dr. Greg Henry at UBC, was part of the International Tundra Experiment (ITEX). Individual plants were tagged, and plant phenology measurements in early June were carried out to corroborate results from the previous summer that did not begin until early July. Likewise, early-season measurements of net CO_2 exchange using static chamber techniques (Figure 1) were carried out to explore key carbon cycling processes during the transition from snow-covered area to bare ground. We also completed the first round of trace gas (methane, nitrous oxide) flux measurements in the ITEX plots. These results, when completed (measurements being done with collaborator Elyn Humphreys, Carleton), will provide comprehensive data showing the net impact of these experimental treatments on greenhouse gas exchange between the land and the atmosphere. These results are crucial in order to understand future feedbacks between the climate system and High Arctic ecosystems.

Considerable work was undertaken on the two lakes at CBAWO including a comprehensive assessment of contaminants in the water and sediments. In addition to water column profiling and water sampling, dissolved greenhouse gases were sampled on several occasions from each lake. We also did depth profiles of these greenhouse gases in both East and West lakes to determine zones of gas production or consumption. Sampling also focussed on collection and analysis of water from East and West Lake and their inflows for analysis of total mercury (THg) and methyl mercury (MeHg), as well as collection of arctic char. Water was collected in each lake and in tributaries. In addition large volume sampling (~200 L) water and ~40 L snow

Figure 1. Automated chamber systems measuring net carbon dioxide fluxes from polar semi-desert communities at the CBAWO. Even the wildlife like to observe research. Photo by Robert Mactavish.

was conducted for the determination of POPs (PCBs and other chlorinated organic pollutants) as well as for perfluorinated alkyl substances (PFASs) in June as well as for water in early August. Soil and vegetation were also collected for analysis of organic contaminants. Landlocked arctic char were collected in early August 2016 but fishing was unsuccessful in Headwater Lake (upstream of West Lake).

THg and MeHg were determined at Canada Centre for Inland Waters (CCIW, Burlington, ON) using a Direct Mercury Analyser while 31 elements were determined by acid digest and ICP-MS. Large volume samples were extracted at the PCSP Resolute Base laboratory. The XAD and filters were subsequently extracted in a clean room at CCIW and POPs were analysed by gas chromatography-tandem mass spectrometry (MS/MS). PFASs were analysed by liquid chromatography-MS/MS. Carbon and Nitrogen isotope ratios ($\delta^{13}C$ & $\delta^{15}N$) were determined by IRMS (EIL, U of Waterloo). Analysis of covariance of the THg data in char was used to assess trends over time using length or $\delta^{15}N$, or interactions with year in the model.

In addition to field activities in 2016, our ArcticNet funded students completed their analyses, writing their theses and publishing their research. A total of six MSc and one PhD theses were completed in 2016. Also, during 2016, we published a substantial number of papers highlighted in our project entry.

RESULTS

Watershed hydrology and biogeochemical studies

The 2016 season was characterized by low snow cover and runoff, conditions that have being increasingly common during the past decade at Cape Bounty. Initial sediment transport indicates that erosion from the 2007 permafrost disturbance across both catchments has decreased substantially, with lower snowmelt, baseflow and rainfall concentrations. These results suggest that the system suspended sediment loads have largely recovered from the permafrost disturbance and the decreased runoff intensity in 2016 is resulting in less overall sediment transport.

Investigations of subsurface water flow indicate highly variable but localized preferential flow pathways. This results in localized delivery of water to the river from slopes, and in the establishment of surface and subsurface discharge points that sustain baseflow. We are evaluating the hydrochemical consequence of these pathways, but initial results suggest that they are important for delivery of dissolved nitrogen and carbon to the streams and rivers.

Preliminary results from the laboratory incubation experiments on water sampled on ponds and subsurface seeps indicate that there is little seasonal change in the dissolved organic carbon (DOC) pool in these surface waters, and that the DOM may be more labile earlier in the summer (early July) relative to later (early August) (Figure 2). Additionally, preliminary analyses of the incubation experiments suggest that the humification index (HIX) (derived from fluorescence measurements) is inversely correlated with lability as determined by the incubation experiments. This suggests that optical characterization in these waters may serve as good proxies for lability.

Results from recently published or submitted studies investigating the influence of seasonal hydrology and physical disturbances on the composition of DOC, reveal that that DOC concentrations in stream in surface water runoff decreased with increasing degrees of disturbance of a watershed, but that the composition of the DOC exported from disturbed watersheds tended to be fresh and more easily degradable (labile) (Fouché et al, in press). This study also showed that rainfall runoff exported high concentrations of fresh and labile DOC. A related study illustrates that permafrost disturbance and late season rainfall also enhance the export of nitrate (an important nutrient) from these watersheds (Lafrenière et al., submitted).

In our more detailed analysis of dissolved organic matter in the streams, we found that the DOC concentration in river waters at the 14 sites ranged from 1.1 to 5.9 mg/L and that of pond water at the six sites ranged from 1.9 to 51.3 mg/L. Both river and pond waters had large variations in DOC and TDN concentrations with location. However, C/N ratios were significantly lower in pond (11±7) than in river waters (19±4). The pond DOM is chemically distinct from the river DOM based on isotope and spectroscopic analyses. Compared to the river water, the pond water DOC had significantly higher ^{14}C and ^{13}C values ($P<0.05$). The ^{14}C DOC ages of the pond waters were estimated to range from 1028-4975 years BP, and those of the river waters were all ≤ 440 years BP. Materials derived from linear terpenoids (MDLT), carboxyl-rich alicyclic molecules (CRAM), and carbohydrates+peptides dominated in 1H NMR and the aromatic+phenolic constituents accounted for less than 6% for all samples. A significant difference in MDLT but not in other three types of constituents could be found between river and pond samples (Figure 3). Compared to the 1H NMR spectra, the diffusion edited 1H NMR showed an increase in the percentage of carbohydrates+peptides and decreases in the percentages of the MDLT and CRAM constituents in all samples. The absorbance and fluorescence-associated indices, indicate that the pond water was significantly fresher (higher BIX), less aromatic (lower SUVA), and less degraded (lower HIX) relative to river samples ($P<0.05$). Fluorescence PARAFAC also show that compared to the river samples, the pond samples showed significantly lower abundances of terrestrial-humic-like components but significantly higher abundances of oxidized-product-like and protein-like components. From the upper to lower reaches of the main channel in the West River, the DOC concentration, C/N ratio, ^{13}C, and the relative abundance of carbohydrate+peptides in 1H NMR increased, and the relative abundance of MDLT in 1H NMR slightly decreased. Comparing the

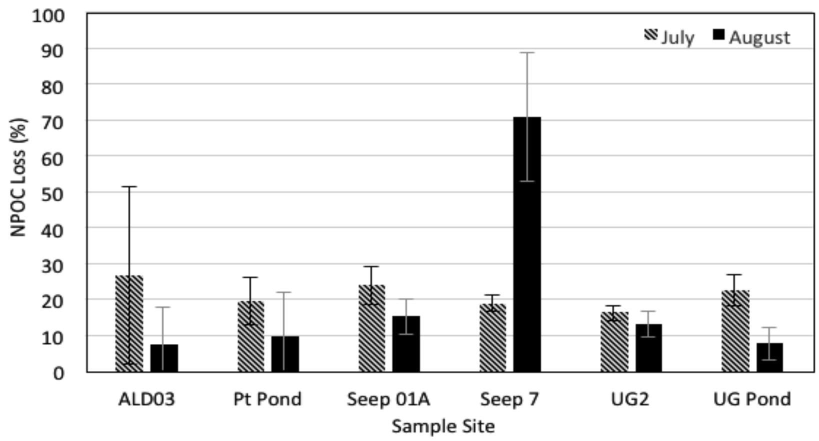

Figure 2. Non-purgeable organic carbon (NPOC) loss (%) over an incubation period of 28 days at 20°C. Each site was sampled at the beginning (early to mid-July) and end (early August) of the 2016 field season. All sites are located at the Cape Bounty Arctic Watershed, Melville Island, Nunavut.

ALD-disturbed ponds and disturbed tributary with undisturbed pond samples, the ALD-disturbed DOM had much less carbohydrates+peptides but more CRAM constituents in the 1H NMR spectra. Also, they had significantly less terrestrial-humic-like fluorescent components but more oxidized-product-like fluorescent components. Particularly, ponds associated with previous ALD showed higher ^{14}C and lower DOC concentrations than other ponds.

Lake physiochemistry

Lake water profiles indicate that the West Lake turbidity has been sustained at high levels since the winter of 2011-12 when two slumps occurred underwater. The result is strongly contrasting water column conditions in the two lakes. Detailed sampling of the bottom waters of both lakes demonstrated localized chemical variations

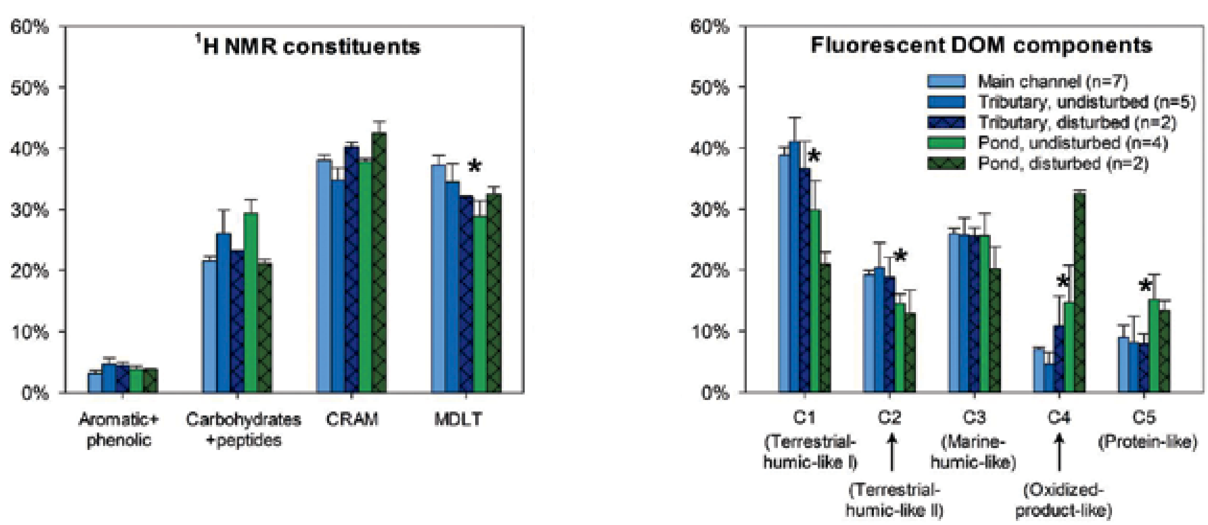

*Figure 3. Different spectroscopic characteristics (mean±SD) of river and pond dissolved organic matter from West River catchment of Cape Bounty Arctic Watershed Observatory, Canadian High Arctic. *Significant difference between river and pond.*

consistent with groundwater seepage. This work was significantly aided by the detailed sidescan sonar survey of the lakes completed in 2015 (Normandeau et al. 2016) and represents the first demonstration of groundwater seepage in a High Arctic lake. We are pursuing further analyses to determine if we can identify past variations (or presence) of groundwater in the lakes to determine the magnitude of role this water source plays in the overall lake system.

Average concentrations of pCO_2 and pCH_4 in West Lake (793±375 uatm and 10.4±19.7 uatm, respectively) were lower than in East Lake (846±109 uatm and 65.0±12.8 uatm, respectively), but all concentrations were above atmospheric equilibrium, suggesting that these two lakes are sources of these two greenhouse gases to the atmosphere. Concentrations of pCO_2 and pCH_4 were similar throughout the water 27 m water column of East Lake, but in West Lake, concentrations of both of pCO_2 increased at 31 m just above the lake sediments, suggesting active microbial respiration in the sediments.

The complete record of water column concentrations of THg and MeHg were reviewed and summarized during 2016 (2008-2015 data). Total quantities (grams) of THg and MeHg were estimated based on the average water concentrations and lake volume. Total MeHg in both lakes gradually increased until 2014, then began decreasing again between 2014 and 2015 (Figure 4). Virtually all of the MeHg is present in the dissolved phase, unlike the THg pools which are primarily bound to particles. This is significant because dissolved MeHg is the form that is more bioavailable for organisms to take up. Actual concentrations of MeHg concentrations continue to be extremely low and comparable in the two lakes (0.01±0.01 ng/L in both).

Mean THg concentrations in arctic char from West Lake continue to be significantly greater than those in East Lake except in 2009 when char were feeding on more pelagic carbon. THg in char muscle is mainly (>90%) in the form of MeHg. Mercury has increased in char from West Lake (4.8 %/yr) while declining in East Lake (-4.8 %/yr). Condition factors [weight (g) x 100 / length $(cm)^3$] and % lipid content in the char have declined significantly in West Lake at 6.1 %/yr (r^2=0.63, P=0.01) with lowest values associated with high turbidity (2013-16). No significant change in condition has been found for char in East Lake.

The two major groups of PFASs, perfluorocarboxylates (PFCAs) and perfluorooctane sulfonate (PFOS) concentrations in Arctic char muscle from East and West Lake were not significantly different. The time series (2008-2015) suggests that PFCAs in char are decreasing at a rate of 31 %/y in West Lake and 22 %/y in East Lake (Figure 5). This contrast with minimum decreasing rates for PFOS of 1.8 %/y in East Lake, while a slightly increase of 0.5 %/y was observed in West Lake.

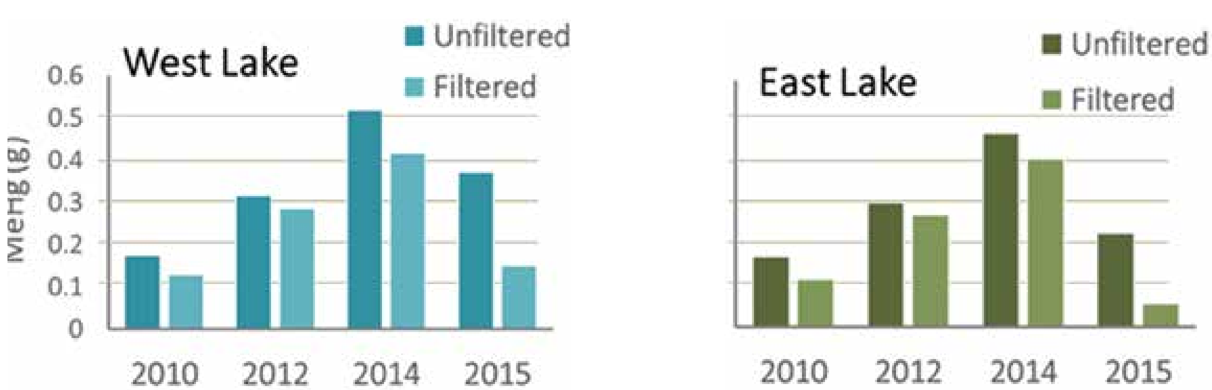

Figure 4. The average total quantity or pool of MeHg in each of the sampling years are shown for West Lake and East Lake.

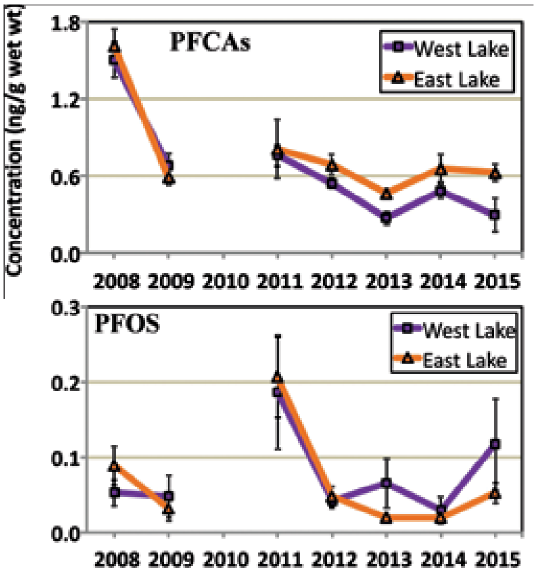

Figure 5. Temporal series of PFCAs and PFOS in West and East Lakes from 2008 to 2015. Data are presented in geometric means±SE of ~15 fishes collected each year.

Figure 6. Area around the ITEX plots showing the enhanced snowfall from the snowfences, and the land landscape during snowmelt. Photo by Sean Arruda.

Terrestrial Ecosystems

Early-season measurements of plant phenology and environmental variables that influence CO_2 exchange (e.g. active layer depth) confirmed our measurements from the 2015 season. Active layer development was delayed in all experimental treatments within the ITEX experiment, even in the control plots (Figure 6, grey line). This is likely due to the extensive effect of the snow fences on snow deposition compared to the surrounding landscape. Even control areas likely received some additional snowfall, and this delayed the onset of plant growth and active layer development relative to control sites outside the ITEX study area. Of the four experimental treatments (not including the outside control) the warmed plots showed the earliest signs of active layer development. This treatment also showed the earliest signs of plant growth (first green leaf), confirming our result from 2015 showing that plant senescence occurred first in the warmed treatment. This has implications for the timing of photosynthesis and carbon uptake. While the experimental treatments had a strong early-season impact on active layer depth and other environmental measurements (e.g. soil moisture), most of these effects were not present by the end of the growing season (Figure 7). Measurements of net CO_2 fluxes from the experimental treatments confirmed the positive impact on carbon uptake and storage of the warmed treatment (Figure 8). Enhanced early-season photosynthesis (compared to the other treatments) allowed the warmed treatment to have the greatest net CO_2 uptake over the entire growing season, even compared to the outside-control, which barely exhibited a net carbon removal from the atmosphere. Interestingly, ecosystem respiration rates (orange bars in Figure 8) differed little across the experimental treatments, suggesting little difference in soil temperature among the treatments, as respiration is very sensitive to temperature (Valentini et al., 2000).

A second remote sensing project focused on novel indices to track vegetation change. The spectral bands prevalent in the optimal 2-band vegetation indices, several were located at the important absorption features observed in the original spectra such as 681.20 nm (pigment absorption), 721.90 nm and 732.07 nm (along the red-edge slopes), 1174.77 nm and 1184.87 nm (water absorption), and 1447.14 nm, 1457.23 nm, 2072.65 nm and 2102.94 nm (cellulose and lignin absorption). When compared with broadband VIs, narrowband VIs exhibited slightly stronger

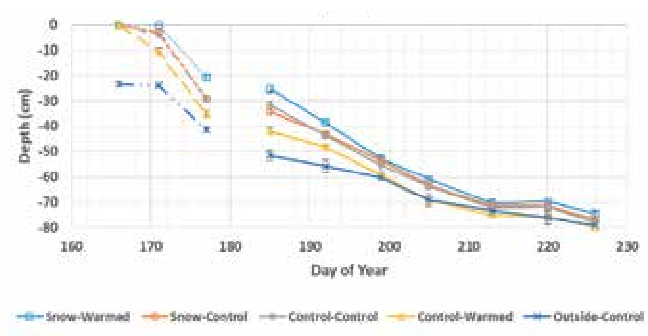

Figure 7. Active-Layer depths in the different treatments including the early season mesurments in 2016 (dashed lines). Note the delay in active layer development in ALL the experimental treatments compared to the outside control.

correlations with green PVC due to the narrow and deeper absorption features sampled by hyperspectral data (Figure 10). Further, spectral indices that incorporated the yellow spectral data of WorldView-2 performed slightly better than spectral indices without, indicating that the yellow channel may be more useful for investigating Arctic vegetation types that often included large proportions of senescent vegetation throughout the growing season.

Finally, a program of research that examined the geomorphic processes leading to permafrost disturbance in periglacial environments led to the development of methodologies for detecting permafrost disturbances (including subsidence and uplift) (Figure 11) and modelling areas susceptible to permafrost disturbance.

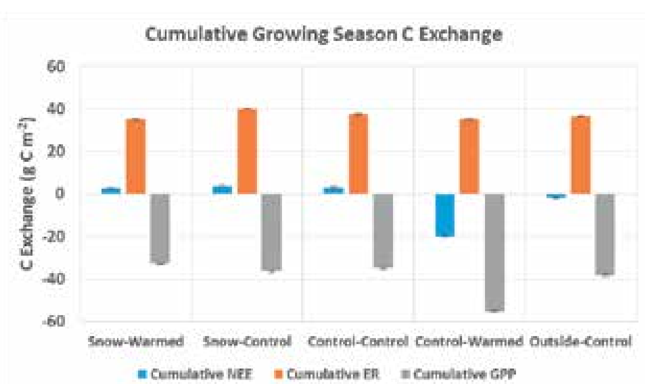

Figure 8. Effects of ITEX experimental treatments on photosynthesis, respiration, and net ecosystem carbon storage over a growing season. Negative numbers are fluxes into the ecosystem.

DISCUSSION

Work at Cape Bounty represents the longest record of comprehensive watershed research in the Canadian High Arctic and has served as a model for the new research program under development at the CHARS station near Cambridge Bay. Results from Cape Bounty are now resulting in multi-year syntheses (e.g., Lamhonwah et al., in press; Roberts et al., submitted) related to rivers, lakes, water quality and remote sensing of vegetation. Research at CBAWO provides key insights into how High Arctic watersheds respond to climate and permafrost change, and will guide future research and provide knowledge for communities and decision makers. Our companion project at the Apex River near Iqaluit reflects this knowledge transfer, through our efforts to

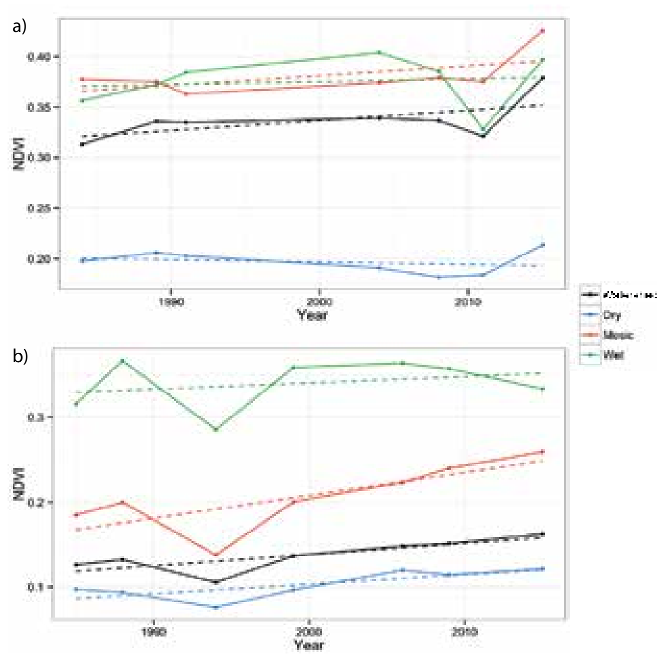

Figure 9. a) NDVI time series by vegetation type in the ARW (1984-2015). The ARW represented in black contains all pixels located in the watershed. b) NDVI time series by vegetation type in the CBAWO from 1985-2015. The CBAWO represented in black contains all pixels located in the watershed.

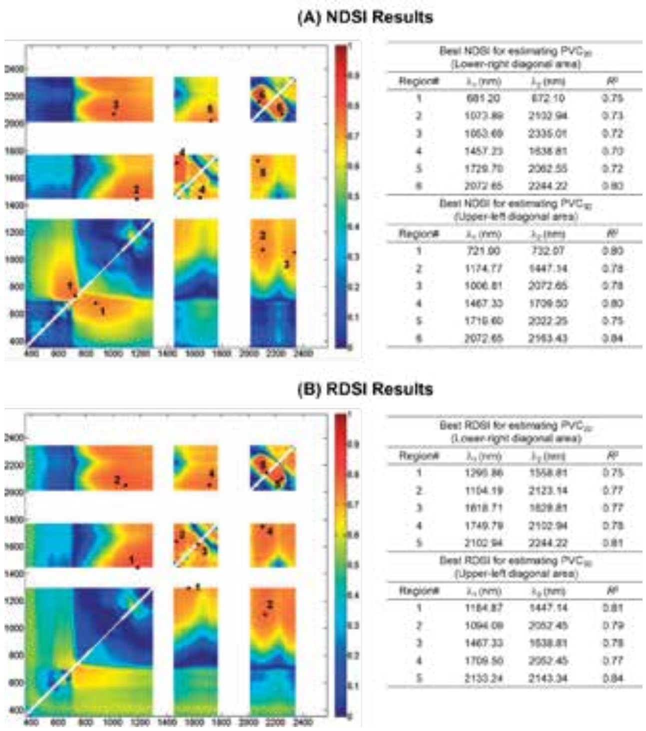

Figure 10. Correlations (R^2) between Hyperion n-derived NDSIs/RDSIs and green PVC. For each corralation map, the x and y axes are the wavelengths of hyperion, respectively; the lower-right diagonal area represents the R^2 between PVS_{2d} and NDSI/RDSI; the upper-left area represents the R^2 between PVC_{3d} and NDSI/RDSI; the regions with high R^2 (>0.7) are numbered and the highest R^2 position in each region is marked by a black square. The tables associated with each correlation map list the optimal band combinations an R^2 values for each region.

develop a sustainable research program and to build capacity in Iqaluit for watershed research.

Hydrological results from Cape Bounty indicate a continuation of reduced snow pack and associated runoff in the spring. This pattern has been in place since 2008 and contrasts strongly with greater snowpack and runoff from 2003-7. The shift in runoff reduces overall flow, but also alters the timing and nature of water quality in this system. Sediment transport is markedly reduced, and suggests an overall recovery of the location to the 2007 permafrost

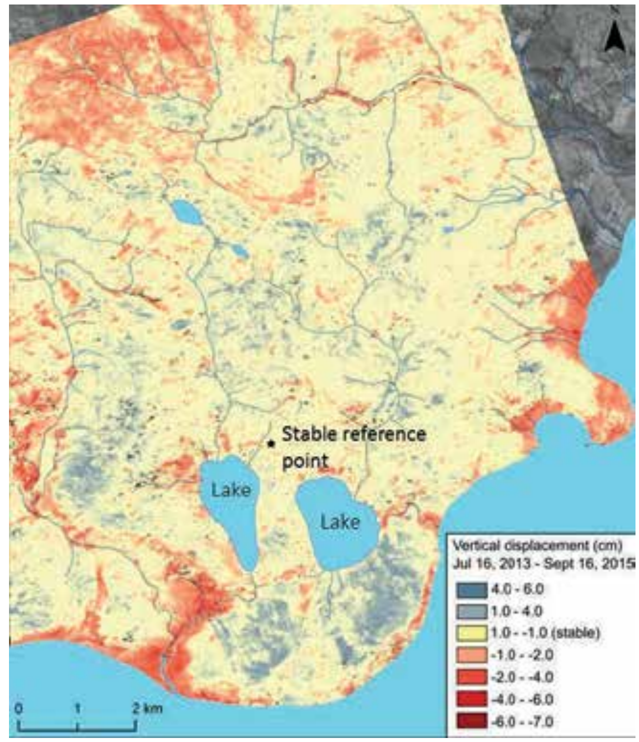

Figure 11. Inter-seasonal relief displacement dedived from DInSAR (2013-2015).

disturbance. Rainfall runoff and sediment transport is more difficult to determine given how infrequent rainfall is at Cape Bounty, but we are now focused on this issue with the Ph.D. work of Casey Beel.

Other measures of water quality show increased mobilization of dissolved components in the streams and rivers. Field research in 2016 shows how these components follow preferential pathways in the thawed soil to the rivers, and this new knowledge will assist in improving our modelling efforts to better predict summer runoff and related water quality. These studies further demonstrate that both permafrost disturbance and late season rainfall likely deliver more labile DOC and inorganic nitrogen derived from either thawed permafrost or enhanced microbial activity. These results are significant as they demonstrate that permafrost degradation, active layer deepening, and increasing rainfall are all likely to trigger changes in the biological productivity and function of aquatic ecosystems.

The disturbance from ALD can significantly alter DOM composition as reflected by the spectroscopic analyses of water samples. Both tributary streams and pond waters shifted their DOM, likely through added nutrients for the microbial activity in water that caused a larger degree of DOM degradation. The stimulation of ALD disturbance to soil and river organic matter degradation has been previously noticed and was considered as important positive feedback to climate warming in the Arctic (Grewer et al., 2015; Pautler et al., 2010).

Down stream of the catchments, the lakes at Cape Bounty also reflect a long legacy of field research focusing on the impacts of watershed change on inflows, changes to the physical and chemical structure of the lakes, and the cycling of contaminants. In particular, we have investigated mercury (Hg) dynamics for many years, and in 2015-16 added a comprehensive assessment of other persistent organic pollutants (PFASs) to the program.

A recent synthesis of the lake physiochemical data (Roberts et al., submitted) indicates that both lakes at Cape Bounty have rapidly responded to climate and permafrost change. The chemical composition of the lakes simultaneously increased by up to 500% for some dissolved elements, particularly between 2012-14. These changes are interpreted to reflect drainage from the deep active layer and demonstrate for the first time that permafrost change can alter large lakes rapidly. We further investigated this change through otoliths (ear bones) of Arctic char and found that the fish were also showing evidence for this rapid change in water chemistry. At the same time, warming and reduced ice cover have improved aquatic conditions and resulted in a shift in primary producers in the lakes (diatoms), so we are now seeing several dimensions of environmental impact from climate change (Roberts et al., submitted).

Concentrations of CO_2 in the surface waters of East and West lakes are always above atmospheric equilibrium, resulting in both these systems being constant sources of CO_2 to the atmosphere. This means that, overall, rates of decomposition of organic carbon in these lakes is greater than rates of primary productivity. Concentrations of CO_2 are higher in the bottom waters West Lake, clearly showing that there is biological decomposition of organic matter in the sediments of this cold lake.

From the long term Hg program, our preliminary conclusion is that increased total Hg inputs into West Lake from permafrost disturbance in its catchment and subaqueous slumping of sediments in the lake itself, have resulted in higher concentrations of Hg in char in that lake. Much higher turbidity in West Lake from 2009 to 2015 compared to East Lake, may be causing food web shifts and reduced food availability to char as shown by the decreasing trends of fish lipid content in fish from West Lake. This may explain the lower than average condition factors for char. Whether this decline in condition of the landlocked char is widespread across Nunavut is not known, but studies of similar size lakes on Cornwallis Island do not show major trends in condition over the same time period. On the other hand we have not studied another lake quite like West Lake so these results may be singular.

Our results for PFASs illustrate the widespread low level contamination by these chemicals which are used in stain repellents and surface coating products and transported to the arctic in the atmosphere from urban areas in North America and Asia. PFCA concentrations in East and West Lake were about 2-fold higher than in two other lakes for which long term data is available (Lakes Amituk and Hazen) while PFOS concentrations were similar. Further work is underway to estimate the river inputs of PFASs and the inventory in the soils, snow and vegetation of the East and West Lake catchments to try to understand the differences between these lakes and those on Cornwallis Island.

Predictions of climate change in the Arctic suggest much warmer temperatures and higher precipitation (likely as snow). One measure of the health of these systems, and an indicator or changes in health in response to climate change, is the net movement of carbon between the land and the atmosphere. Ecosystem health, in turn, is a critical indicator of whether an ecosystem can provide the critical "service" of e.g. clean water to residents of the north. Our results suggest an interesting interaction between the warming and snow accumulation in terms of their impact on the net carbon balance of Arctic landscapes. Warming alone should lead to longer growing seasons, greater photosynthesis, and increased net CO_2 removal from the atmosphere (a negative feedback on subsequent climate change). Enhanced snowfall could negate some of the impacts of warming by delaying the onset of plant growth in the early part of the growing season. In terms of the carbon balance, both warming and enhanced snowfall will likely influence the net carbon balance by altering plant phenology, not by significantly changing environmental factors such as active-layer depth.

Given summer mean temperatures are near freezing in the Canadian High Arctic, a shift in summer air temperatures of a few degrees can cause a several-fold change in the total amount of warmth available for plant growth, resulting in major changes to vegetation structure, plant productivity, biomass, species diversity and shifts in zonal vegetation boundaries (Walker et al., 2005). This warming is also having an immediate impact on permafrost, hence terrain stability.
Our research examines the response of terrestrial ecosystems at high latitudes to warming. This research is extremely important, as these ecosystems are highly sensitive to warming, yet it remains unclear as to how these ecosystems will respond in terms of stability and productivity, but also in the context of ecosystem feedbacks to global climate (Bonan et al., 1995). Collecting *in situ* measurements of biogeophysical variables, including their relationship to carbon exchange, and relating these measurements to remote sensing data collected at multiple scales is essential to understanding the response of these ecosystems to warming. Deriving biophysical measurements from remote sensing data and through statistical modelling is the only feasible method to examine (and predict) these processes over large spatial extents and through time. This research at the field level and scaled up to satellites' synoptic scales, provides knowledge of the relationships between climate warming and terrain stability and ecosystem processes. With this understanding, we are able to make informed and knowledgeable policy decisions related to development in the North. This research will also help us develop adaptation strategies for communities and resource industries living and operating in Canada's Arctic.

Apex River

ACTIVITIES

The 2016 season was our fourth with the Apex River project and built on previous success in engaging the community, developing capacity for water research in Iqaluit, and establishing long term partnerships. The Nunavut Research Institute (NRI) played a key role in the planning, coordination, and oversight of field research activities from May 16, 2016 (onset of snowmelt) to September 28, 2016 (onset of freeze-up). NRI research intern Jean Allen and summer student Anika Bychok participated in all routine data collection; including water sampling for metals, dissolved organic carbon and nutrient analyses, stream discharge measurements, and microbial indicator monitoring over the duration of the field campaign.

In addition to personnel, NRI provided office and laboratory space, field and lab equipment, ground transportation (truck and ATV), and other resources to support all aspects of the program. NRI also delivered wilderness first aid and laboratory safety training to project technicians, worked with researchers to develop field schedules, and we communicated daily with team members (e.g. via SPOT and satellite phone) to ensure their safety and arrange field transportation.

In partnership with NAC ETP student field assistants, we conducted skidoo-based snow water equivalent (SWE) surveys across the 51km^2 Apex River watershed. A stratified random sampling design was used based on results from the 2015 field season. A terrain-based model of snow-accumulation was developed using digital-terrain analysis and 2016 snow surveys results.

We also installed hydrometric and micrometeorology instrumentation, which will be used to conduct detailed monitoring of snowmelt onset and progression in 2017. The micrometeorology tower (Figure 12) includes sensors for air temperature, relative humidity, wind speed/direction and net-radiation, as well as a camera for capturing images of snow covered area and a cellular modem for remote data acquisition. Snowmelt lysimeters (Figure 12) were retrofitted in 2016 with heat lines to ensure ice-free drains in spring 2017 and these installations should allow for detailed monitoring of plot-scale snowmelt timing and magnitude in conjunction with snowpack temperature profiles and micrometeorology conditions.

Our lack of knowledge of the spatial distribution of groundwater inputs to surface waters limits our understanding of the importance of groundwater to aquatic ecosystem function, and prevents an adequate assessment of the impacts of environmental change on freshwater ecosystems in arctic environments. From June 28th to August 28th, 2016 we conducted field studies in the Apex River watershed to both define the spatio-temporal patterns to subsurface inflows to the surface waters during summer baseflow recession period (Objective 1); and determine the physical factors that control the storage and routing of water from hillslope recharge areas to surface waters (Objective 2). To realize our first objective, we undertook fine scale mapping (1-m resolution) of surface water temperature and conductivity along four river segments (lengths ranging from 500 to 700 m) and along the margins of 2 lakes (Figure 13). Local variations in temperature and conductivity were used to infer the location of subsurface inputs to the river. At a selection of sites, we installed mini-piezometers to determine hydraulic gradients at river and lake margins. To realize our second objective, we instrumented a hillslope-stream sequence with a network of 28 piezometers equipped with water level sensor-loggers to track the flow of water across the hillslope (Figure 14). Additionally, we (i) used intrusive methods (e.g., soil cores, falling head test, depth to frost table measurements) (Figure 15) and non-intrusive methods (e.g., mapping of microtopography) to determine the three-dimensional architecture of the hillslope deposits; and (ii) collected a total of 81 water samples from different water sources (i.e., groundwater wells, stream, lake and rain) for analysis for electrical conductivity, stable water isotopes ($\delta^{18}O + \delta^{2}H$) and Dissolve Organic Carbon (DOC) to determine source water contributions and hydrological connectivity across the hillslope.

The Iqaluit Analytical Services Unit (IASU) has been offering the Environmental Sampling and Analysis Training program since 2010.Each year has been a very different experience and the characteristics of that

Figure 12. Apex River meteorology station.

Figure 13. Surveying the river with a tow instrument that records temperature and electrical conductivity.

Figure 14. Field site with installed piezometers that provide measurements of the water level below the soil surface.

Figure 15. Soil coring in the Apex River watershed.

experience are defined to a great degree by the students themselves. There are often features, that stand out and this year was no exception. For the first time all students completing the course (and all the teachers too) were women. The ages, education levels and experience of the trainees ranged from high school student to government employee working on a post graduate degree (Figure 16). Training, as part of the ArcticNet project and Environmental Sampling and Analysis, introduces students and researchers to laboratory quality assurance, laboratory accreditation, and the international accreditation standard ISO/IEC 17025. Regulatory agencies often require that testing be done by accredited laboratories as it ensures the competency to produce credible and reliable results that pass legal scrutiny (Figure 17). Furthermore, the facilities at the IASU located at the NRI were used as a staging ground for other ArcticNet researchers to collect and collate project specific water samples.

RESULTS

Basin-wide SWE in 2016 was determined to be 24 cm ±3 cm (n=193, Figure 18). The reported confidence interval of 3 cm represents 12.5% of the mean, indicating the high sampling intensity required to achieve reliable estimates of basin-wide mean SWE. This reflects the very large spatial variability of snow depth and SWE due to wind-redistribution throughout the snow accumulation season in this rugged landscape. A terrain-based model of snow accumulation resulted in three landscape unit types with significantly different snow accumulation regimes (ridges, valley floors and hillslopes, Figure 19). This terrain based classification can be used to further refine future survey designs.

Surface profiling of natural groundwater tracers (temperature; electrical conductivity) revealed local anomalies and reach scale variations indicative of subsurface flows to the channel (Figure 20). Terrain

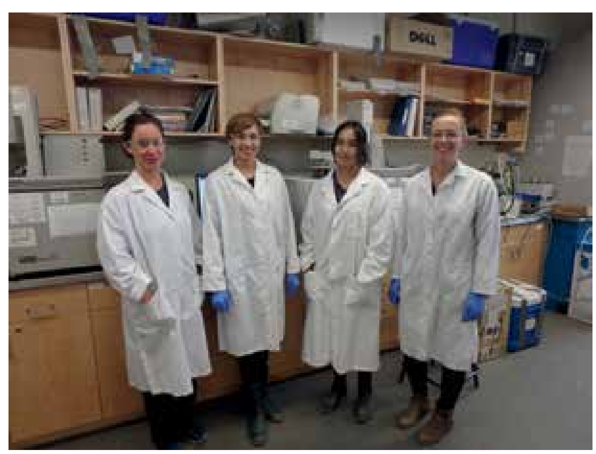

Figure 16. ASU ArcticNet researchers and students at NRI, Summer 2017: from left to right: Marie-France Gagnon, Jean Allen, Lena Korgak and Anika Bychok. Photograph taken by ASU Research technician, Sonja Koster.

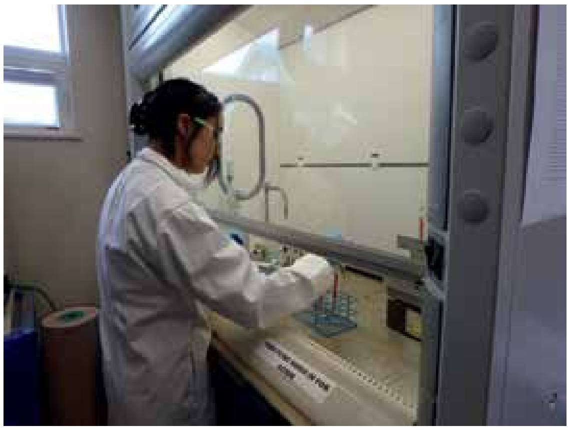

Figure 17. Lena Korgak, preparing water samples at the IASU. Photograph taken by ASU Research technician, Sonja Koster.

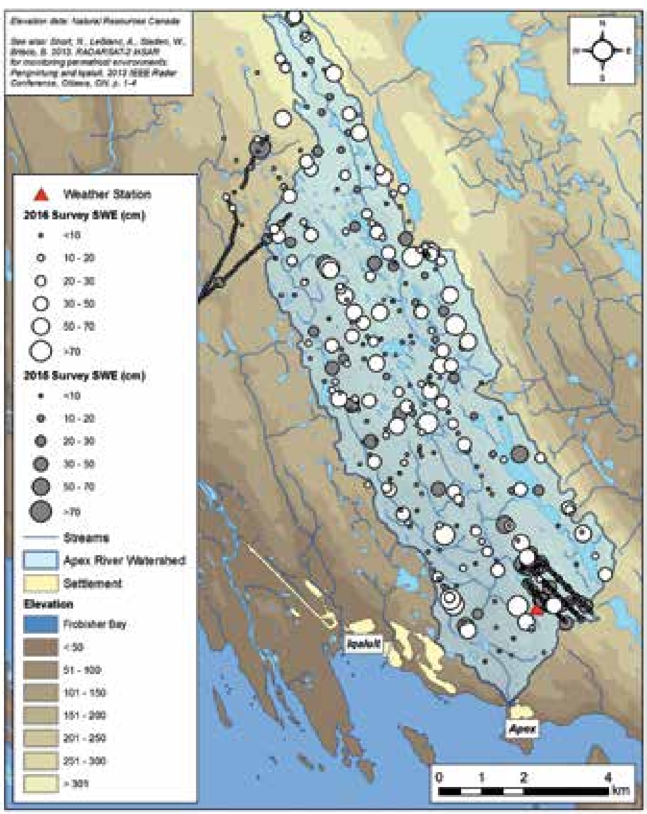

Figure 18. Snow survey network and results, Apex River 2016.

analysis will be conducted to interpret the results of our local scale mapping of natural groundwater tracers in relation to detailed knowledge of surficial deposits and topography. Analysis of hillslope groundwater flow patterns is ongoing but initial results indicate that subsurface flow was concentrated in the middle of the studied hillslope with dynamic relationships related to the hydrogeomorphic characteristics of the hillslope deposits (Figure 21). The analysis of water samples should provide important insights into the dynamics of subsurface flow at this site. Measurements of frost table depths revealed that the extent of frost table lowering varied substantially across the hillslope. Further analysis will investigate the relationship between groundwater flow and the evolution of frost table depths during active layer thaw.

DISCUSSION

The lack of snow hydrology research and monitoring activities in the Apex River watershed has led to a relatively poor scientific understanding of seasonal and inter-annual patterns of snow accumulation and melt and their contributions to the timing and magnitude of annual runoff in this basin. Snow redistribution by wind and its interactions with

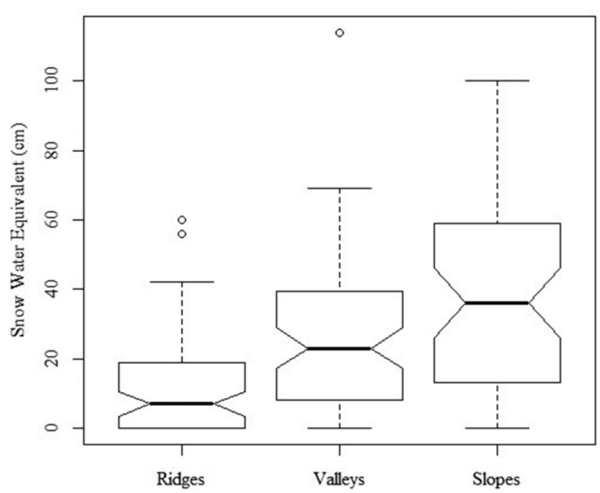

Figure 19. Snow accumulation results by landscape type.

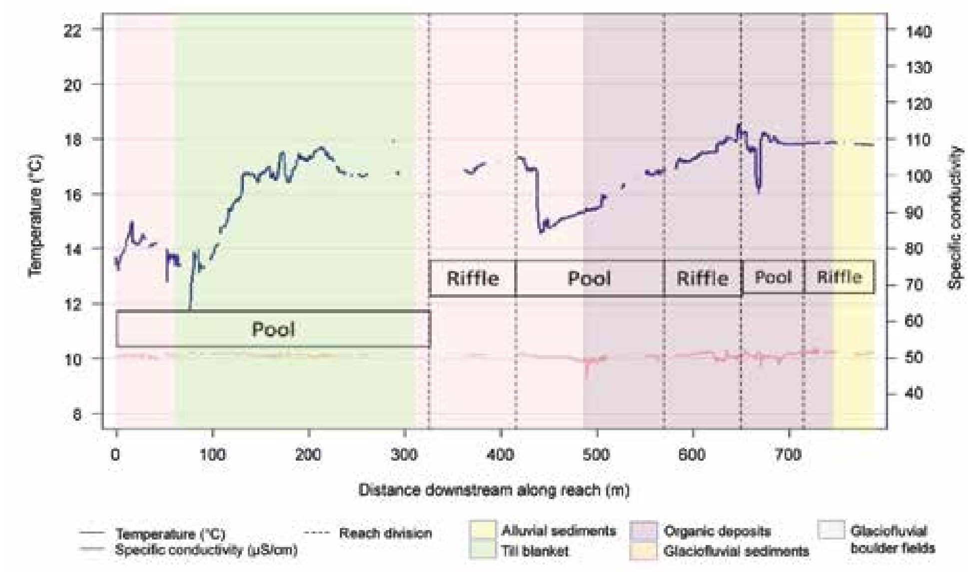

Figure 20. Downstream temperature and electrical conductivity measurements from tow surveys, indicating inflows from slopes.

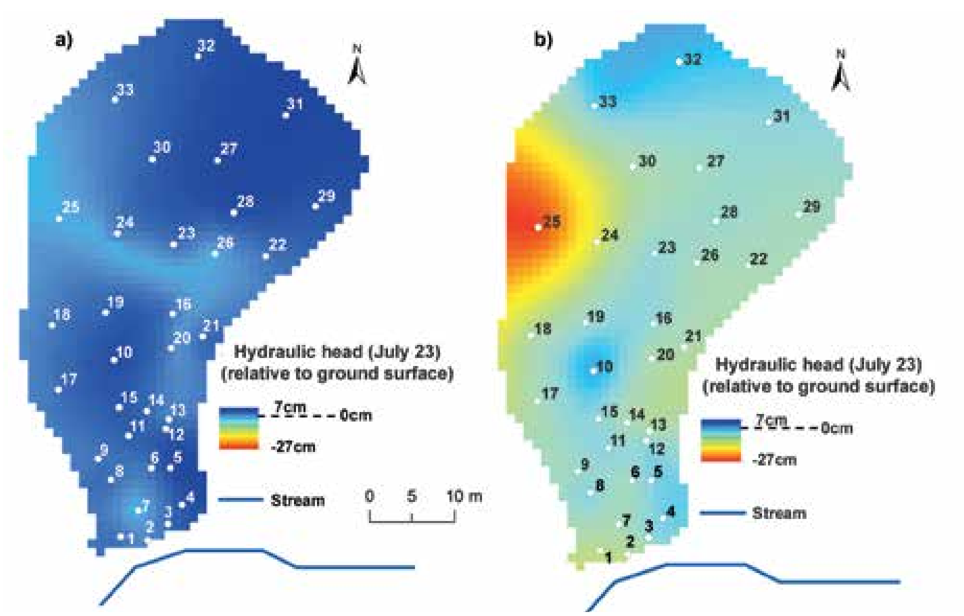

Figure 21. Example of hydraulic characteristics of slope in Apex River.

terrain morphometry leads to extreme spatial heterogeneity of snow cover in this landscape, making it difficult to reliably estimate average SWE across the basin. Since snow accumulation and melt is the dominant driver of the annual runoff regime for the Apex River, improper estimates of basin-wide end of season snow water equivalent is a major source of uncertainty in short- to medium term flow-forecasting approaches. Our 2016 results build on those from 2015 and demonstrate tangible progress towards improvement of SWE sampling protocols for the Apex River watershed using a terrain-based classification approach. Subsequent work will focus on testing of a physically-based, gridded snow redistribution model with the goal of further refining sampling efficiency and accuracy of areal SWE estimates.

Groundwater inputs to surface waters support critical ecological functions in streams and lakes (Brunke and Gonser, 1997). Groundwater discharge (baseflow) provides a buffering mechanism for natural variations in stormflow. Groundwater also exerts a strong local influence on the physical and chemical characteristics of surface waters (Edwards, 1998, Gooseff et al, 2008), and thereby on the specific habitats and life histories of aquatic organisms. Yet in most catchments (including the Apex River) the local-scale distribution of groundwater fluxes to surface waters is unknown (Hinton, 2014). This lack of knowledge was highlighted by the Intergovernmental Panel on Climate Change (IPCC) as a key limitation for assessing climate change impacts on aquatic ecosystems (Settele et al, 2014). This issue is particularly relevant for northern catchments where permafrost degradation is expected to significantly impact hydrological processes. The dearth of knowledge about local groundwater fluxes to surface waters is equally limiting for ecosystem approaches to water resources management (Council of Canadian Academies Expert Panel on Groundwater, 2009). Thus, the outcome of this research is also relevant to the management of northern water resources, where for example the City of Iqaluit has recently proposed drawing water from the Apex River to meet its future needs for freshwater.

CONCLUSIONS

Research activities for this project during 2016-17 have remained high and are increasingly reflecting long term perspectives from sustained monitoring and research at the Cape Bounty field site. These results are of tremendous importance for determining the response of High Arctic landscapes, water and ecosystems to climate and permafrost change, and contribute key basic scientific knowledge to improve our understanding of issues and challenges related to water security in the region. ArcticNet support and networking has significantly supported this activity for over a decade and has resulted in arguably the only integrated High Arctic research program in the world.

The value of this work has translated into the establishment of our Apex River project, focusing on direct community and research capacity growth on a water body of tremendous importance to the residents and City of Iqaluit. There are specific and current water security issues related to the Apex River, and our work contributes to knowledge and decision making. Knowledge and expertise gained at Cape Bounty feeds directly into the Apex River project, and we are continuing to work towards sustaining a long term research program with partners. To date, we have secured further funding from the CHARS program to extend these efforts to Arctic College and we will continue to work further to maximize the potential of this emergent water research "hub" at NRI and in Iqaluit.

We anticipate that the 2017-18 period will represent both advancement of our state of the art research to understand the implications of climate and permafrost change. Our research will also offer further syntheses of long term datasets in the rivers, sediment transport, contaminants and remote sensing indicators of change. We will further contribute to several chapters in the IRIS 2 volume, and have accepted several invitations to submit reviews in leading research journals. Additional students will join our group and we are planning further engagement with the Resolute community, through social media and town visits.

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PROVIDING CLIMATE SCENARIOS FOR THE CANADIAN ARCTIC WITH IMPROVED POST-PROCESSING METHODS

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ABSTRACT

Planning and adapting to a warming Arctic require the best information on the possible climate change over the next several decades. This information is typically obtained from physically-based models of the Earth climate system which simulate its response to increasing greenhouse gas concentrations. Usually a large number of model simulations are needed to take account of different greenhouse gas emission scenarios, of differences in model physics formulations and of the natural variability of the climate system. While climate scientists have high confidence in the projected global-average range of warming, there is greater uncertainty in regional and local changes relevant for decision-makers, particularly in the Arctic region where natural components such as sea ice and permafrost exist. One limitation comes from the resolution of the models. For example, the highest resolution for model simulations currently available for the Arctic region is ~ 25 km, a scale still too coarse to capture many of the important local-scale influences on climate. For this and other reasons, climate simulations must be post-processed, i.e. downscaled and statistically adjusted to obtain statistical properties similar to those of observed time series. The objective of this project is to provide the Canadian Arctic decision-makers and communities with scenarios for temperature, precipitation, wind speed and other climatic variables and indicators. The state-of-the-art post-processing methods employed aim at correctly representing extreme weather events and take into account observational uncertainties as well as inter-variable correlations. Wind scenarios, a major development of this project, are used notably for assessing climate change impacts on sea ice regimes and coastal erosion. The project also includes active linkages to several ArcticNet proposals addressing climate change impacts on Arctic ecosystems and hydrology.

KEY MESSAGES

- The project's main objective is to provide ArcticNet Integrated Regional Impact Studies (IRIS) related projects with climate scenarios that benefit from state-of-the-art post-processing methods and most recent regional model simulations over the Arctic.
- Available CORDEX simulations for the Arctic and North American domains, reanalyses, and observational datasets (observations, interpolated) were gathered.
- Reference periods (historical and future climate) were defined and validated by the IRIS 4 coordinating team.
- A list of relevant climate variables and indicators was created and validated by the IRIS 4 coordinating team. A total of 21 temperature-based indices, 17 precipitation-based indices and five snow-depth-based indices were selected.
- Temperature and precipitation based climate indicators from the various CORDEX simulations and reanalyses were estimated and compared to indicators estimated from closest station series.
- Comparison of mean climate indicators over the reference period showed that: 1) most RCMs performed well in simulating temperature indices, with the exception of TXx index, where a cold bias was observed in RCMs and in reanalyses; also reanalyses outperformed the ensemble mean of RCMs for most temperature indices; 2) ensemble mean of RCMs and reanalyses showed similar performance for precipitation indices, some RCM simulations outperforming the reanalyses for precipitation extremes (R95p, R99p and RX1day).
- An approach has been developed to combine reanalyses and stations climate indicators values across the study region based on Ensemble Optimal Interpolation (EnOI). Historical reference climatology (one for each climate indicator) was created and preliminary validation shows that these could be used to assess climate indicators at ungauged sites for historical climate.

- Different reference datasets and strategies have been tested for determining the optimal method for generating wind and temperature scenarios at sub-daily frequency.
- Inter-variable physical consistency with univariate post-processing (quantile mapping) has been investigated for minimum and maximum daily temperatures.
- An ensemble of six basic scenarios (wind/temperature) with good uncertainty coverage have been generated for Hudson Bay area (~ 30-km spatial frequency), covering the 1979-2100 period.
- A method to select climate simulations which provide realistic sea ice cover was developed.
- Upgraded version of the numerical wave model allows the simulation of the wave-ice dynamics under realistic conditions. The tests conducted over a short-term period give consistent results and have allowed the validation of the marine and coastal indicators. These indicators will allow quantifying the predicted changes in waves and ice climate at key points along the Hudson Bay coasts, a direct contribution to the second IRIS 4 Assessment Report.

OBJECTIVES

Project objectives are organized into: 1) upstream objectives (directly oriented at improving methods for designing basic scenarios); 2) basic scenarios development; and 3) downstream objectives (application of basic scenarios and derived climate indicators). More specifically, the objectives are:

1. Upstream objectives

a. Inventory and acquisition of available observational products for wind speed, and assessment of selected post-processing methods;
b. Sensitivity of scenarios to reference datasets and development of scenarios combining different reference datasets;
c. Assessment of multivariate post-processing methods.

2. Basic scenarios development

a. Synthesis of upstream methodological results and development of basic scenarios;
b. Assessment and characterization of daily extremes in observational products, simulations and scenarios.

3. Downstream objectives

a. Modeling of wave and fast ice dynamics in Baffin Bay and Hudson Bay;
b. Provision of climate indicators and analysis for the IRIS 4 report and elaboration of the climate chapter.

Please note that objective 1.b has been changed from its original formulation as explained in previous progress report.

KNOWLEDGE MOBILIZATION

- Seven presentations at scientific conferences.
- Skills and exchange knowledge with university students [2 M.Sc. students supervised by P. Grenier; 1 undergraduate student and 1 M.Sc. supervised by Prof. Mailhot].
- C. Barrette and R. Brown collaborated to a journalistic investigation by C. Pollon (independent journalist, based in Vancouver). The investigation topic is adaptation actions in Nunavik in a context of climate change. The collaboration consisted in questions and answers, support and climate data provision.

INTRODUCTION

The main goal of this project is to provide ArcticNet IRIS related projects with climate scenarios that benefit from state-of-the-art post-processing methods. Improvements (relative to previous IRIS scenarios) include the use of new simulation results from regional models, coverage of marine areas, consideration of the uncertainty on reference dataset in the post-processing, and the development of scenarios for wind speed. Special attention will be devoted to extremes in precipitation and temperature as well as to inter-variable dependences.

This progress report presents the activities and results obtained during the second year of the project. Despite some adjustments that has to be made to some objectives (e.g. for obj. 1b), globally the project progresses as initially planned. Major improvements have been made in defining reference climatology for historical climate (obj. 1b), development of future projections of climate indicators (obj. 2a).

ACTIVITIES

Dataset gathering, preliminary analysis, selection of reference periods and return periods

- New datasets, for example for snow cover, were gathered and added to datasets already considered in the study as well as new simulations (OURANOS-CRCM5 and CORDEX-RCM ensemble) of simulations.
- Discussion with the end users were initiated to identify and validate the historical and future periods to be considered in the forthcoming analysis.
- Discussion with the end users were initiated to identify the most relevant return periods for extreme events (e.g. wave height) in impact and adaptation studies.
- Comparison of mean projected relative changes over Quebec of mean annual temperature and mean annual precipitation from CMIP5 ensembles and available CORDEX simulations was performed to evaluate if projected changes from CORDEX simulations cover the range estimated from CMIP5 ensemble.

Activities are reported for each of the sub-objectives listed in the OBJECTIVES section:

1.a Univariate wind speed post-processing

- CFSR and ERA-Interim reanalysis have been compared with in situ data (ship measurements from ICOADS database and AHCCD records) over Hudson Bay.
- Analogue method was investigated as a possible wind post-processing method.
- Two different approaches have been investigated for producing sub-daily scenarios, the first combining daily quantile mapping and domain-scale analog search to ensure high spatial coherence, and the second performing sub-daily quantile mapping to ensure high temporal continuity.

1.b. Sensitivity of scenarios to reference datasets and development of scenarios combining different reference datasets

- Comparison of temperature and precipitation climate indices from the various datasets (reanalyses, records, and interpolated datasets) was made to estimate the differences between these datasets in assessing the historical climate of Arctic.
- Optimal Interpolation (OI) and Ensemble Optimal Interpolation (EnOI) were implemented to combine the gridded climate indicators over Canada estimated by the four reanalyses with the corresponding values estimated from station records. OI was used to combine individual reanalysis to station values while EnOI was used to combine all four reanalyses to station values.

- Cross validation was performed. Various calibration and validation station networks were created. For each calibration network, climate indicators were estimated using OI and EnOI over Canada. Climate indicator values at stations of the validation network (not used to create the EnOI gridded climate indicator datasets) were then compared to corresponding values from station records.

1.c Assessment of multivariate post-processing methods

- Assessment of multivariate methods for the pair of variables wind/temperature has been changed to an analysis of the limitations of univariate methods for post-processing of daily minimum and maximum temperatures (Tmin and Tmax). These variables are often required by end users, and it is known that univariate post-processing methods may lead to unphysical results where Tmin > Tmax. The objective is to assess the frequency of occurrence and amplitude of these cases, and then to determine whether a multivariate approach is mandatory.

2.a Synthesis of upstream methodological results and development of basic scenarios

- Preliminary analysis of quantile mapping method using different reanalyses datasets as reference was first realized. Climate indicators were then estimated and compared to values from station records in a cross validation experiment. The option of bias correcting the simulated reference climate for each index directly with stations measurements was also investigated.
- Preliminary work has been done to develop a method to select climate simulations (among a large ensemble) according to the realism of the simulated sea ice cover since this variable has a crucial impact on air temperature.
- Daily precipitation and daily temperature from CORDEX simulations were corrected (quantile mapping method) using five reanalyses as reference dataset. Indices were computed and then compared to indices from station records.
- Basic scenarios have been developed for wind components and temperature over Hudson Bay area at a 3-hour time step for the 1979-2100 period.

2.b Assessment and characterization of extremes

- The performance of the quantile mapping method for extreme indices over the IRIS 4 domain was tested.
- Cross validation of bias corrected extreme indices (quantile-mapping method) was realized with respect to corresponding indices estimated from recorded series.
- Changes between future (2040-2064 and 2076-2100) and historical periods (1980-2004) have been estimated for all extreme indicators and each RCP.

3.a Modeling of wave and fast ice dynamics in Baffin Bay and Hudson Bay

- Waves-in-ice interface was implemented in the two-dimensional numerical model WaveWatch III (WW3).
- Tests were conducted under realistic conditions in the Hudson Bay to evaluate the ability of the model to reproduce the complex waves-in-ice dynamics and identified possible improvements to the actual formalism. Idealized simulations were also performed to investigate the sensitivity of the coupling interface to different attenuation and breaking schemes.
- A floe size and thickness redistribution scheme has been implemented and tested to study the effect of wave-induced breaking on the floe size distribution and validate parameterizations used in WW3.
- Marine and coastal indicators were identified to characterize the historical and future waves and ice climate in the near-shore area of the Hudson

Bay. As the indicators chosen to describe the ice conditions under changing climate have never been used in the past, preliminary simulations were realized with help of reanalysis data to assess the feasibility of their computation and their relevance.

- A high spatial resolution landfast ice model has been implemented in some key locations along the Hudson Bay. Simulations are planned for the next year.
- For specific short-term events (current climate), the fragmentation process simulated by the wave-ice coupling interface will be validated with help of passive microwave data (NOAA/NSIDC) of the sea ice concentration within the Hudson Bay.
- Ocean simulations within the Hudson Bay have been conducted based on results from upstream objective 2a (climate scenarios). These simulations will be used to force the wave model (ice concentration, ice thickness, current and sea level) and assess the waves and ice climate evolution. Efforts will be made to evaluate the impact of the post-processing methods used to produce climate scenarios on the wave generation. The simulations will cover the historical (1980-2004) and future periods (2020-2100).

3.b Climate indicators for upcoming IRIS reports and ArcticNet projects

- The list of climate indicators was revised, completed and validated by the end users. This list now includes climate indicators related to snow cover.
- Various prototypes of maps, graphs, box plots, violin plots and tables, illustrating and synthetizing climate indicators, have been developed. A main concern was the representation of uncertainties on projected changes and on reference climate.
- These prototypes are actually analyzed by selected end users to see if they address their needs and comply with their requirements. A key issue here is to provide the information in simple and readily forms that also satisfy accuracy requirements of scientific communication, for instance in terms of communicating result uncertainty. A final selection of the prototypes will be made shortly.
- Coastal sites where ice simulation should be done were selected. This list was established based on various criteria related to the presence of communities, of transport infrastructures, known erosion problem.
- Different options as to how future change in extreme events will be illustrated were investigated.

RESULTS

The following paragraphs summarize the main results obtained during the SECOND year of the project for each research objective listed above:

Dataset gathering, preliminary analysis, selection of reference and return periods

- Two gridded daily snow water equivalent (SWE) datasets were obtained for evaluation of the CORDEX simulations: the SnowModel Pan-Arctic Reconstruction (Liston and Hiemstra, 2011), and the Blend5 multi-product dataset (Mudryk et al. 2015). Gridded daily snow depths from the Canadian Meteorological Centre (CMC; Brown and Brasnett 2010) and from SnowModel Pan-Arctic Reconstruction have also been obtained. Finally, we are in the process of obtaining updated daily snow depth and bi-weekly snow survey data from the Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques (MDDELCC). Table 1 gives the list of snow datasets gathered for the project.
- Table 2 provides the list of new simulations added to the project dataset.

- Historical period is defined as the 1980-2004 period (25 years) while two future periods will be used: 2040-2064 and 2076-2100 (both 25-year periods).
- Extreme values, for example of wind and waves, will be estimated for 2- and 10-year return periods. These return periods were selected since they are, according to end users, the most relevant return periods of current applications.
- Results of the comparison of mean projected relative changes over Quebec for mean annual temperature and mean annual precipitation from CMIP5 ensembles with available CORDEX simulations showed that the projected changes from CORDEX simulations cover the range of values estimated from CMIP5 ensemble. This support the use of the regional CORDEX ensemble.
- Figure 1 presents the position of the coastal sites where preliminary simulation od ice cover will be done. The exact list of selected sites will be establish based on results from these preliminary simulations.

1.a Univariate wind speed post-processing

- Comparison of CFSR and ERA-Interim reanalysis with in situ data (ship measurements from ICOADS database and AHCCD station records) over Hudson Bay area, showed that both reanalysis have strengths and weaknesses. CFSR was selected for convenience because of its spatial and temporal resolutions.
- Analogue method was discarded (discontinuities in post-processed series).
- Investigation of datasets and methods lead to the following methodological choices for wind post-processing: 1) CFSR was selected as the reference product for gridded scenarios; 2) wind components will be treated separately and can be recombined afterwards; 3) quantile mapping (QM) will be applied separately for each sub-daily block rather than at daily time scale; 4) standard quantile mapping will be adapted to preserve long-term trends of simulated series.

Table 1. List of datasets related to snow gathered for the project.

Dataset name	Type/variable	References
SnowModel Pan-Arctic Reconstruction (1979-2008)	Daily snow depth and water equivalent (m)	Liston and Hiemstra (2011)
Blend5 (average of MERRA, ERA-I-Land, Crocus-ERA-I, GLDAS-2, GlobSnow)	5-dataset average daily snow water equivalent and spread (m)	Mudryk et al. (2015)
CMC snow indices	Snow indices based on snow depth from CMC stations.	Brown and Brasnett (2010)

Table 2. List of new simulations gathered for the project.

Regional Climate Model-Simulation domain	Driving fields (GCM or reanalysis)	Period (RCP)	Number of simulations
OURANOS-CRCM5	CCCma-CanESM2	1950-2005 (Historical) 2006-2100 (RCP 4.5)	2 2

Figure 1. Position of the coastal sites where simulations of ice cover will be done.

1.b Sensitivity of scenarios to reference datasets and development of scenarios combining different reference datasets

- Preliminary results from cross validation are promising. They suggest that OI and EnOI can provide realistic values of climate indicators at ungauged sites (i.e. with no historical records).

1.c Assessment of multivariate post-processing methods

- Preliminary results with standard univariate post-processing methods indicate a frequency of occurrence of about 1-2 % of unphysical cases (Tmin > Tmax) over Hudson Bay (only one scenario). Options and parameters of the post-processing algorithm are being tuned to minimize number of occurrence of such cases; forthcoming analysis will determined if multivariate post-processing is mandatory for this application.

2.a Synthesis of upstream methodological results and development of basic scenarios

- Results of the post-treatment of CORDEX daily precipitation and temperature series (quantile mapping method) using five reanalyses as reference dataset indicate that the more appropriate reference dataset for precipitation is obtained by using ensemble mean of raw CORDEX simulations averaged over the reference period.
- Basic scenarios were developed for wind components and temperature over Hudson Bay area at a 3-hour time step for the 1979-2100 period. It was shown that the selected ensemble offers a good coverage of uncertainty (compared with 196 other simulations) and a checkup algorithm has demonstrated that these scenarios are plausible in terms of many statistical properties (extreme, annual, diurnal cycles, spatial continuity, etc.).
- For temperature indicators (except Nthaw, TXx, TXn, TNx indices), CORDEX ensemble mean post-treated using quantile mapping approach with Global Meteorological Forcing Dataset for Land Surface Modeling (GMFD; Sheffield et al. 2006) as reference historical dataset was the more appropriate choice.
- Results showed that the ‘quality’ of the reference dataset characterizing the historical climate is crucial for post-treatment.
- Results obtained in objective 1.b suggest that the comparison of reanalyses and station records through EnOI may provide good quality reference datasets (further investigations are however necessary before a systematic implementation).
- Preliminary results regarding the role of sea ice cover on future climate change indicate that rejecting simulations with unrealistic sea ice concentration during the reference period lead to a noticeable reduction of the uncertainty of future warming for sea ice transition months; for example, for June, the interval width of future warming (maximum minus minimum warming over 95 years among an ensemble of 83 simulations) is then reduced from 9.8 °C to 6.9 °C.

2.b Assessment and characterization of extremes

Assessment of upstream method results in terms of extremes

- Figure 2 provides an example of results (projected changes of RX1day). This figure shows that increases associated to RCP8.5 are larger than the corresponding values for RCP4.5. Projected changes are also larger for the 2074-2100 period than for the 2040-2064 period for both RCPs and the differences between the two RCPs are larger for the 2074-2100 period compared to the 2040-2064 period. Similar features are obtained for all climate indicators.

Estimation of changes in Pr and T extremes in the basic scenarios

- Results indicates increased extreme warm days, less severe coldest annual temperatures and warmer cold extremes. An increase in extreme precipitation is also projected, especially for RCP 8.5.

3.a Modeling of wave and fast ice dynamics in Baffin Bay and Hudson Bay

- Simulations realized in the Hudson Bay under realistic conditions showed that the wave-ice coupling interface added to WaveWatchIII, and included in the new released version of the code (WAVEWATCH III Development Group, 2016), performed well. The attenuation and breakup processes produce a realistic marginal ice zone, with increasing size of sea ice floes from open water to ice covered area where a sharp shift in size marks the beginning of the central pack. A smooth transition is observed in wave amplitude and period across this specific sea ice environment.

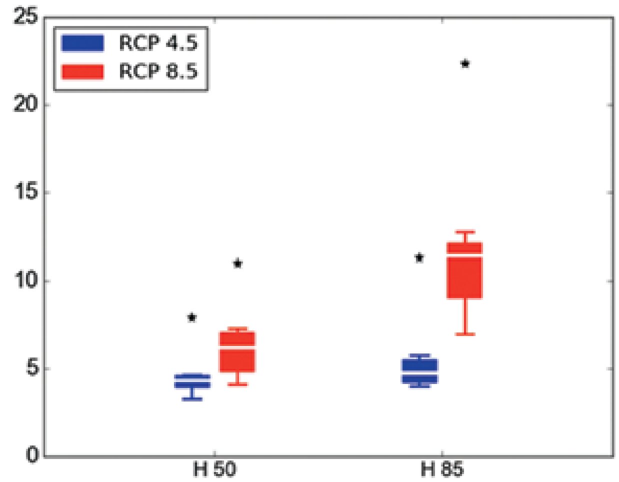

Figure 2. Box plots of the changes in mean regional value over IRIS 4 of Rx1day indicator between 2040-2064 (H50) and the reference period (1980-2004), and between 2074-2100 (H70) and the reference period. The box plot values correspond to the various simulations.

3.b Climate indicators for upcoming IRIS reports and ArcticNet projects

- The list of climate indicators was updated. Table 3 presents the list of climate indicators related to snow cover.
- A list of marine and coastal indicators was selected to assess the historical and future waves and ice climate is presented in Table 4. These indicators will be evaluated at the near-shore area of the twenty (20) key points identified along the Hudson Bay coasts (which included

Table 3. List of selected snow cover climate indicators.

Label (units)	Description
SDCSC (Julian day)	Starting date of continuous snow cover
EDCSC (Julian day)	Ending date of continuous snow cover
SCD (days)	Snow cover duration
Sdmax (m)	Maximum snow depth
DSDmax (Julian day)	Date of maximum snow depth

Table 4. Selected marine and coastal climate indicators.

Symbol (units)	Description
WAVES	
2-,10-yr H_s (m)	Significant wave height having a 2- and 10-year return period 10 km offshore of selected points along the coast.
ICE	
A_{max} (%)	Annual maximum ice area coverage over the domain.
t_{onset} (julian day)	The date when the total ice coverage over the domain becomes greater than 30%.
t_{melt} (julian day)	The date when the total ice coverage over the domain falls below 30%.
A_n (%)	Daily ice concentration averaged over the domain.
V_n (m)	Daily average ice thickness over the domain.
h_c (m)	The critical average thickness required for the ice to resist flexural break-up induced by the most energetic waves simulated over the winter season, at selected points along the coast. If the ice is thicker than this value, it will likely stay consolidated.
t_{start} (julian day)	The last day of the calendar year when sea ice is broken by waves 10 km offshore of selected points at the coast *or* the date at which the ice thickness remains above 12 cm for at least ten consecutive days (*if no wave-induced breakup observed*).
t_{end} (julian day)	The first day of the calendar year that sea ice has been broken by waves 10 km offshore of selected points at the coast *or* the date at which the ice thickness remains below 12 cm for at least ten consecutive days (*if no wave-induced breakup observed*).
h_{coast} (m)	Average ice thickness during the safe period 10 km offshore of selected points at the coast.
$t_{\mathrm{end}} - t_{\mathrm{start}}$ (days)	The maximum number of consecutive days without any breakup 10 km offshore of selected points on the coast.

local communities). The first six indicators were previously used in past studies (Ruest et al., 2016; Senneville et al., 2013), while the remaining five are new. They were thus computed, tested and validated with the help of benchmark simulations.

- List of wind indicators is presented in Table 5.
- Representation of future change of extreme events will be made by mentioning the return period in future period associated to a given intensity over the historical period. For instance, a 20-year extreme intensity in historical period, could become a 5-year return period intensity in a given future period. This form of presentation of how extreme will change in future climate was selected as it is more evocative and suggestive

Table 5. Preliminary list of selected wind climate indicators.

Label (units)	Description
sfcWind (m/s)	Annual average of daily mean wind speed
sfcWindMax (m/s)	Annual average of daily maximum wind speed
sfcWindMaxAnn (m/s)	Annual maximum of daily maximum wind speed
sfcWindDir (°)	Annual prevalent direction of daily mean wind
W_wind	Annual number of windy days (with maximum wind speed > 5.5 m/s, corresponding to numbers 4+ on Beaufort scale)
W_damage	Annual number of days with potential damage from wind (with maximum wind speed > 20.8 m/s, corresponding to numbers 9+ on Beaufort scale)

than to simply say for instance that 30-year return period intensities will increase by 15%.

- Prototypes of maps, graphs, box plots, violin plots and tables, illustrating and synthetizing climate indicators, have been identified and will be analyzed by selected end users to see if they address their needs and comply with their requirements.
- Forcing scenarios RCP4.5 and 8.5 will be treated separately. Therefore results about the changes in climate indicators will refer to two future periods (2040-2064 and 2076-2100) and two RCP (RCP4.5 and 8.5).
- While presenting maps and graphic examples to some selected end users, the IRIS coordination team prepares various visual proposition of the “Results” section of the drivers of change chapter. The expected feedback will help the coordination team in elaborating the most appropriate and appreciated visual format for this core section of the chapter.

DISCUSSION

1.a Univariate wind speed post-processing

This part of the research project is complete. Datasets and methods relevant have been analyzed, and main choices made for the development of basic scenarios.

1.b Sensitivity of scenarios to reference datasets and development of scenarios combining different reference datasets

Climate indicator datasets in historical climate based on EnIO are interesting candidate to define the historical climate over IRIS regions. Therefore, it is planned to use these datasets as reference datasets in historical climate. They could be used for bias correction of the CORDEX simulations. Such bias corrections would applied to climate indicators (and not daily series). Further analysis need to be done however before actually implementing such procedure. Forthcoming work will focus on analyzing the performance of OI and EnOI for the northern region since current analysis was done considering the Canadian territory. Post-processing of daily series (precipitation and temperature) remain an open issue at this point.

1.c Assessment of multivariate post-processing methods

A univariate approach has been applied to the pair of variables Tmin/Tmax over Hudson Bay in order to evaluate if multivariate post-processing is necessary to correct unphysical cases (Tmin/Tmax >1) or this could be done by simply tuning standard univariate algorithm. Ideally, this work will lead to the publication of a peer-reviewed paper.

2.a Synthesis of upstream methodological results and development of basic scenarios

Defining reference datasets for historical climate is a key issue especially in Northern region where station network sparsely cover the territory. As mentioned in the result section, Ensemble Optimal Interpolation (EnOI) seems a promising method for defining such reference datasets. Preliminary analysis of quantile-mapping post-treatment of daily temperature and precipitation series using different reanalyses as reference dataset was first realized. Climate indicators were then estimated and compared to values from station records. Results show that the 'quality' of the reference dataset characterizing the historical climate is crucial for post-treatment.

2.b Assessment and characterization of extremes

Mean indices values over Arctic estimated from climate simulations and reanalysis daily precipitation series were similar and close to corresponding values estimated from stations series for most climate indicators. Values estimated from the NRCan gridded dataset at closest grid-points to stations were generally smaller than corresponding station values for indices related to precipitation intensity but were similar for indices related to the frequency of occurrence of precipitation. The comparison between climate models also showed that Canadian models outperformed the other models over the Arctic. Comparison of climate mean of winter precipitation and RX1day index over the reference period for the Arctic stations and the corresponding closest grid points showed that some models even outperformed the NRCan gridded dataset. This last result is important and demonstrated that, as expected, interpolated precipitation datasets should be used with caution in regions with low station density.

3.a Modeling of wave and fast ice dynamics in Baffin Bay and Hudson Bay

The wave-in-ice model proposed by Williams et al. (2013a,b) was implemented in the two-dimensional numerical framework WW3. This interface allows both the attenuation of incident wave energy by sea-ice, whether through conservative (scattering) or non-conservative (viscous) processes, and the ice fragmentation in the marginal ice zone. Although energy scattered at the edges of the floes must be conserved, both forms of attenuation are for now considered as a wave energy loss within the model. Study is being conducted to evaluate the consequences of applying an isotropic or anisotropic redistribution scheme to the scattered wave spectrum, which could have major impacts over the wave-ice coupling (Squire and Montiel, 2016). Further tests are needed to quantify this impact and ensure the consistency of the results. Improvements have also been made in the fragmentation process, which allows two breakup criteria that each act preferentially on distinct ice thickness range. Parallel work carried on the floe size distribution and the probability of a wave-induced ice breakup will, in this sense, help to guide the next development steps. The benchmark simulations conducted in the Hudson Bay under realistic conditions have showed that unphysical features observed in the fragmented ice area (i.e. unbroken thin ice) were solved and that the wave-ice interface implementation was improved. The upgraded version of WW3, that included the important physical mechanisms at play in the waves-ice interaction, gives a first numerical platform to evaluate the risk of observing ice fragmentation by waves near coasts and its evolution with respect to historical and future climate.

3.b Climate indicators for upcoming IRIS reports and ArcticNet projects

The writing of the climate drivers section (part of the "Regional drivers of change" chapter) has already begun in parallel to the climate indicators refinements and calculation completion. The complete draft of the chapter including the regional climate and socio-economic drivers of change is expected for October/November 2017 with presentation during the Arctic Change event that will be held in Québec City in December 2017. Along with the IRIS report a climate atlas is planned to be produced. This atlas will include all climate indicators produced through this project and the climate drivers from the IRIS report will link to this atlas for supplementary material and figures.

CONCLUSION

Climate indicators have been identified and validated by end users. Indices related to rainfall occurring during winter and to snow depth will be integrated in the coming year.

Results have shown that multivariate post-processing method adequately correct biases in simulated correlational structures. However, applying multivariate methods to two or more variables can be very complex (for example for wind components and temperature). Therefore, in order to simplify the approach, development related to objective 1c. has focus on tuning univariate post-processing methods in order to minimize unphysical or non-plausible elements of the post-treated scenarios. Present and future investigations will look at identifying the conditions when univariate methods can be applied.

Analysis of wind products and potential post-processing methods led to important technical choices for wind/temperature scenario development.

Partner projects have been provided with improved climate scenario. For example, trend-preserving post-processing (Gennaretti et al. 2015) helped constructing temperature scenarios used by ArcticNet project "Effects of Climate Shifts on the Canadian Arctic Wildlife: Ecosystem-Based Monitoring and Modelling" (Gauthier et al. 2016).

Tests simulations conducted in the Hudson Bay with the improved version of the two-dimensional operational wave model showed that the model performed well. The marine and coastal indicators selected to assess the evolution of the waves and ice climate were tested and verified over short-term period. The generation of waves for the selected reference periods (historical and future) are planned during the next year and will provide for the first time important information for coastal planning and safety in the North.

Climate extremes, wave and wind climatology are frequently requested from IRIS stakeholders but never fully responded up until now. In the case of extreme events climatology and wave climatology previous IRIS assessments did not address these issues. Hence, the current project directly contributes to fill many of these knowledge gaps. It highlights the importance of a thorough evaluation of the selected climate products and the need to find and assess existing post-processing methods that suits the needs of a specific project. The project also exemplifies the challenges in producing scientifically rigorous climate indicators.

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THE ARCTIC SNOWCOVER: SENSITIVITY, CHANGE, AND IMPACTS ON TERRESTRIAL SYSTEMS, WATER RESOURCES AND COMMUNITIES

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ABSTRACT

Snow is a keystone characteristic of the Arctic, with important controls on, and interactions with permafrost, lake and river ice cover; wetland and stream hydrology; vegetation, wildlife habitat including caribou, fish and waterfowl. Rapidly changing climate is resulting in dramatic transformations to the arctic snowcover. The best documented change is the shortening of the snow season. Although in many regions the snow season is ending earlier in the spring, in others it's starting earlier in the fall, and in some cases resulting in a longer snow season. In addition to changes in snow season duration, other changes in snow depth are also likely to be changing across the circumpolar Arctic. Local scale changes that directly impact human communities, infrastructure and wildlife such as caribou, fish and waterfowl have not been well described. There is an urgent need to address this limitation. Critical knowledge gaps are obvious and there is an urgent need to better understand changes in snow and the impacts on communities, infrastructure, and to steer public policy and the development of natural resources.

KEY MESSAGES

- Snow plays a key role in many aspects of the arctic environment and it is changing rapidly in response to a warming climate, and related changes in shrub cover and winter precipitation. Understanding the impacts of these changes is required to understand many aspects of the terrestrial arctic, including vegetation, permafrost, streamflow, and lake levels for example. However, these cannot be studied in isolation, but there is a need to consider the integrated effects of each.
- This project is focused on understanding these complex interactions through a well-designed program that combines multi-disciplinary field observations, remote sensing and high resolution modelling.
- The 2016 spring and summer period was extremely unusual, with the lowest end of winter snow cover since 1991 and one of the earliest and most rapid melt periods on record. This resulted in a long snow-free period, with unusually deep active layer thaw. This may be the new normal in the near future.
- We have calibrated a Cosmic Ray Soil Moisture system, for the first time in Arctic conditions, and we expect that it provide a unique methodology for monitoring the Arctic. This data set will be important for model and remote sensing validation.
- We are carrying out a field program over the 2016/17 winter to test the use of two types of Cosmic Ray sensors to measure snow on the ground. These are expected to provide a new and unique data source to document the changing Arctic.
- We have further demonstrated the utility of an Unmanned Aerial System (UAS) to map snow depth and snow covered area, and when combined with modelled snow density, allows the mapping of snow water equivalent in winter and during spring melt.
- We continue to make excellent progress in quantifying the links between the abiotic landscape and understanding shrub sap flow and evapotranspiration.
- Eddy covariance observations of water and energy is ongoing. This is one of the few such measurements in Arctic Canada and provides key information to understanding the links between vegetation and hydrology. This will also provide a key model validation data set.
- We have made significant progress in modelling snow cover using SnowModel. This will allow us to consider future changes and links between, climate, shrubs, snow, hydrology, and permafrost for example.
- Soil and snow measurements at Trail Valley Creek continue to be used for validation of the

NASA Soil Moisture Active Passive (SMAP) landscape freeze/thaw product.

OBJECTIVES

We are on track and continue to pursue our original objectives to:

1. Determine past changes in climate, shrubs and snow cover for tundra regions of the Western Canadian Arctic,
2. Document the associations between weather, shrubs, active layer moisture/temperature on snow cover formation and melt,
3. Characterize the interactions and feedbacks between snow and shrubs,
4. Conduct modelling experiments with improved snow models to document the contrasting roles of climate, shrubs, and BC on snow cover over the past decades and under future climate scenarios.

KNOWLEDGE MOBILIZATION

- 27 presentations at scientific conferences
- Three interviews with online, print and broadcast media
- One meeting with the Fisheries Joint Management Committee (FJMC) in the Inuvialuit Settlement Region to provide updates on our research program
- One meeting with the Wildlife Game Council in the Inuvialuit Settlement Region to provide updates on our research program
- Meetings with the Dept. of Transport Inuvik to Tuktoyaktuk Highway to discussion hydrological issues related to the ITH
- Through the Government of the NWT (GNWT Wilfrid Laurier Partnership, we have numerous meetings with NWT policy makers and/or decision makers. This includes meetings with Environment and Natural Resources; Department of Transport; Aurora Research Institute. Baltzer and Marsh are members of the GNWT-Laurier Partnership Science Committee and meet monthly.
- Two HQP meetings with NWT students

INTRODUCTION

Snow is a keystone characteristic of the Arctic, with important controls on, and interactions with, active layer temperature and thickness; permafrost processes such as ice wedge cracking and rapid lake drainage; lake and river ice cover; wetland, lake and stream hydrology; terrestrial ecology and biogeochemistry including vegetation, wildlife habitat and carbon and energy cycle processes; and aquatic ecology including key fisheries. A rapidly changing climate is resulting in dramatic transformations to the arctic snow cover (Vaughan et al., 2013). Although changes in arctic snow cover have been documented at large scales (Derksen and Brown, 2013), local scale changes that directly impact human communities, infrastructure and wildlife such as caribou, fish and waterfowl, have not been as well described. There is an urgent need to address this limitation. Critical knowledge gaps are obvious at both the large and small scale, and are indicated by poor modelling results. For example, satellite observations of spring snow cover show much earlier snow free conditions when compared to multi-model ensemble consensus (Derksen and Brown, 2013). Shi et al. (2015) documented earlier start of spring snowmelt, but later spring melt runoff in the western Canadian Arctic. The reasons for both are not well understood, but the direct effects of increasingly warming temperatures and altered precipitation are likely not sufficient to explain the observed changes in the snow and streamflow regimes. Contributing factors might include increasing area of tundra covered by shrubs for example as this can result in conflicting changes, including decreased albedo and hence increasing melt, reduced wind speed and decreased melt, and trapping of more blowing snow resulting in deeper snow cover (Liston and Hiemstra, 2011; Liston et al., 2007) and delayed melt in shrub patches. Although in some cases shrubs result in a longer snow-covered season (Menard et al., 2012), the actual effect of shrubs on snow cover is dependent on shrub properties, shrub patch size and the location of the patches on the landscape. Shrubs also have direct impacts on the spatial and temporal patterns in energy fluxes (Endrizzi and Marsh, 2010) and therefore active layer temperature and thickness (Blok et al., 2010), moisture, watershed runoff, and terrestrial ecology. Existing models are unable to explain this delayed spring melt runoff (Shi et al., 2015) that has been described in the Western Arctic despite increasing spring air temperature, decreasing snowfall, and earlier start of snowmelt. There are key knowledge gaps related to factors controlling shrub patch location (in stream valleys or at the base of slopes below snow drifts for example) and expansion, and the impact of this on snow cover through controls on blowing snow transport and deposition. Unravelling these competing effects and interactions of changes in climate, shrub expansion, remains an important challenge acknowledged by the IPCC, the Canadian Polar Commission and Polar Knowledge Canada. Improved understanding of the integrated arctic system will lead to the improved predictive tools that are required for improved future climate projections, and to consider the implications of a changing arctic climate on key aspects of the arctic environment (snow, permafrost, hydrology, ecology), built environment (cities, towns, industry, and supporting infrastructure), and social systems. Changes in snow will have many impacts on northern aboriginal communities that rely on over snow transport for recreation and hunting, and depend on country foods that rely on snow, including fish, caribou, and waterfowl. Given the importance of snow in the regional climate system and to hydrology, snow models play an important role in climate modelling, and land surface models must include snow to consider the effect of the snow-albedo feedback. To address these research needs, the overall goal of this project is to develop an improved understanding of past changes in snow cover and spatial and temporal variations in current snow, shrubs and active layer. Building on these, we will develop an improved ability to predict future changes in arctic snow cover in response to the integrated impact of several environmental

ACTIVITIES

Time frame and study area: Field work, with researchers on site, was carried out from April to September 2016. Winter field trips to Trail Valley Creek (TVC) were also carried out in in mid-December 2016, end of January 2017, and a planned trip at the end of March 2017 for sensor removal, data downloads, and snow surveys at five cosmic ray stations. During the April to September period we carried out observations across the TVC watershed (58 km^2), and focused additional measurements in the Siksik Creek sub-watershed (1 km^2). In addition, many of our instruments recorded key data during the winters of 2015-16 and 2016-17. These include: multiple weather stations; eddy covariance stations; time lapse cameras; a soil moisture and snow water equivalent network using cosmic ray sensors; eddy covariance systems; soil temperature and shrub tilting network; and other sensors and loggers. However, as these systems were unattended over the winter periods, there were occasional data collection problems with snow and ice limiting the accuracy of the data and a few cases of battery or instrumentation failure. Although not directly part of our ArcticNet project, we have been carrying out complementary measurements at a forested watershed close to the Inuvik Airport to allow comparisons to a fully forested basin that may be similar to our main TVC study site in the future. Our CFI Changing Arctic Network (CANet) project is now fully funded and will result in additional upgrades to our field instrumentation, including excellent AC and DC power to improve winter instrument performance, over the next year.

Camp Infrastructure: Our science activities were directly supported by the further development of the camp infrastructure at the main TVC camp (Figure 1) through CFI and other funding, including a second weatherhaven, a seacan, and satellite internet access. These updates were required to increase camp sleeping and work space, improve AC electrical power supply to ensure use of numerous computer systems, complex data loggers, and data archiving abilities, and to improve cooking, hygiene, and safety. This was urgently required to house scientists from our ArcticNet project as well as other related projects and international collaborators.

Our CANet-CFI project will result in additional upgrades to the camp infrastructure over the next year.

Research: Intensive field and lab work focused on end of winter snow cover, snowmelt and changes in snow covered area over the melt period; summer soil moisture and active layer thickness; eddy covariance measurements; and detailed vegetation measurements. Details include the following:

Automatic Weather, soil and snow stations (AWS[3]):

- Data was retrieved from four AWS[3]s, over tundra, short shrub-tundra, tall alder shrub and white spruce forest land covers. Measurements included: air temperature and relative humidity; wind speed and direction; snow depth; soil temperature;

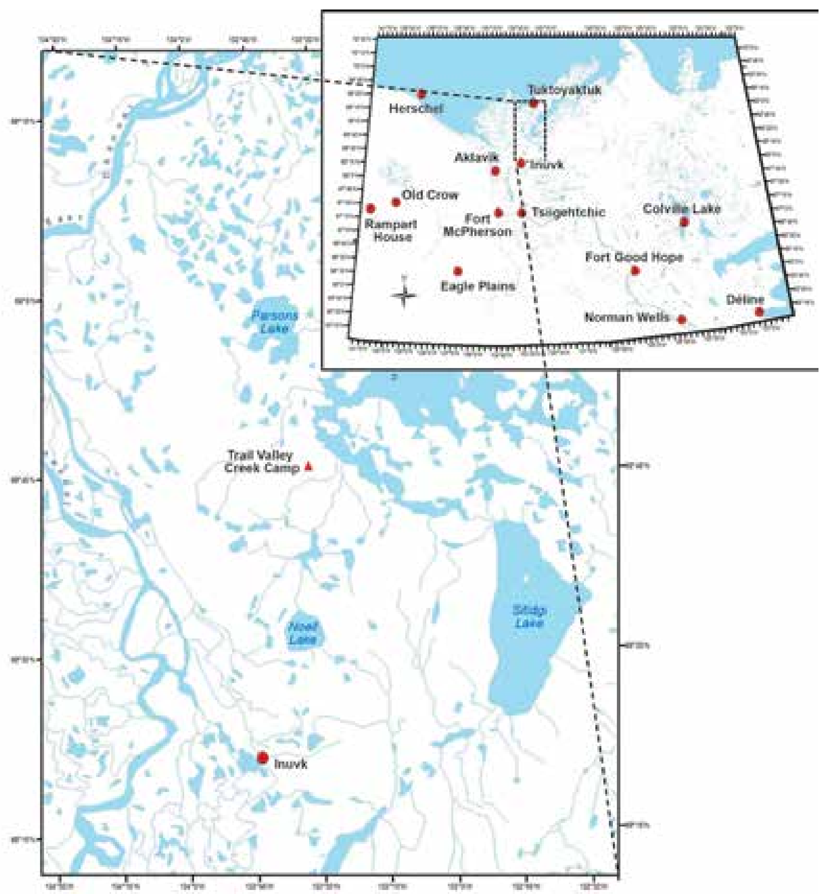

Figure 1. Trail Valley Creek research watershed, showing location in the western Canadian Arctic.

incoming/outgoing short and long wave radiation; and soil moisture.

- Alter shielded Geonor precipitation gauges were located in the lower reaches of the basin and in a nearby sheltered forest clearing. A digital snow pillow was co-located in the forest clearing.
- Four cosmic ray sensors, CRS-1000's, were located at short shrub, forest and tundra sites to measure snow water equivalent and soil moisture. While one system of eight linked SnowFox cosmic ray stations were located across a shrub patch which develops a deep snow patch in the winter as it traps blowing snow.
- The Environment Canada, Meteorological Service of Canada AWS[3] at TVC is co-located with one of our AWS[3], operated throughout the study period and these data are available in real time.

Streamflow:

- Environment Canada, Water Survey of Canada, operated their streamflow station at TVC throughout the spring, summer, fall of 2016. These data will be available in the spring of 2017.
- Streamflow was observed for Siksik Creek using a weir installed in August 2015.

Snow:

- Snow surveys were carried out in April 2016, prior to the start of melt, by B. Walker, P. Mann and others, at sites across TVC. These sites have been measured annually since 1991 allowing a comparison of spring 2016 snow to the 1991-2016 record.
- Snow surveys were also carried out within Siksik Creek prior to melt, and during the melt period, by the same team as noted above, in order to document end of winter snow cover and its relationship to shrub patches and terrain, in much greater detail, and to document the changes in snow cover extent during melt.
- An eBee Unmanned Aerial System (UAS) was flown extensively to image snow cover at the end of the melt period and during the melt period. Four imaging options were available, RGB, Near-infrared, Multispectral, and Thermal Infrared imagers (only one can be flown at a time). Using the RGB imager, we obtained high resolution images (a few cm in horizontal resolution) for all Siksik Creek watershed at the end of winter and throughout melt. In late August, we flew the UAS to map vegetation patterns and Normalized Difference Vegetation Difference (NDVI) and to obtain a snow free digital elevation model.

Soil Moisture:

- Active layer soil moisture variation was measured at various scales and focused on several different approaches. The CRS-1000B cosmic ray instruments offers many advantages as they integrate soil moisture over a relatively large sampling region (approximately covering a circle 200 m in radius around the sensors), but have not been validated for organic rich soils typical of the many areas in the Arctic. This large integration region is advantageous for both hydrological and remote sensing studies. Traditional point based methods are limited to sampling regions of 10s of cm^3 and therefore very large errors occur due to the very high spatial variability of soil moisture observed in this region. In addition, we sampled soil moisture with an extensive network of soil moisture sensors within the footprint of the cosmic ray sensors, and soil moisture observations along several long transects. Along with the soil moisture observations, measurements of shrub presence and frost table depth were also taken. During analysis of the CRS-1000B data, it was clear that there were issues with sensitivity and the soil depth sampled. Ongoing analysis is considering various reasons for this, and devising methods to minimize the errors.

- A model was derived for estimating the spatial variability of soil moisture using RADARSAT-2 data and ground observations.

Active Layer thickness:

- Analysis of the detailed active layer thickness surveys carried out by Post-doctoral Fellow D. Keim and undergraduate student Evan Wilcox in Siksik Creek over the entire 2015 summer are ongoing.

Modelling:

- Post-doctoral fellow, Dr. Ally Toure, who arrived at Laurier on January 4, 2016, has been testing SnowModel, a snow modelling system which is composed of four components (a meteorological distribution model, a surface energy balance model, a snow properties model, and a blowing snow model). SnowModel is installed on the Compute Canada high performance computer. Dr. Toure has been testing all aspects of SnowModel, and visited the model developer, Dr. Liston at Colorado State University, and had other extensive discussions with Dr. Liston. To date the model works very well when compared to various TVC data sets, but it is clear that it underestimates the depth of snow drifts that develop on steep slopes and in shrub patches. Dr. Toure is working with Dr. Liston to determine the need to integrate am existing model component called SnowDens3D, into SnowModel.

Shrub vegetation:

- *Alnus viridis* (green alder) has unique potential to drive change relative to other shrub species growing in tundra systems north of Inuvik, NT. This work aims to understand the constraints for and consequences of alder shrub growth in this low-arctic system.
- This work provides a unique dataset regarding the constraints on alder expansion at two spatial scales, furthering our understanding of shrub patch dynamics and expansion and providing useful information for climate change and hydrological modeling in the North.
- To determine constraints on the distribution of green alder at the landscape scale a land cover classification was developed by C. Wallace and others to identify shrub patches (discrete shrub communities) on the landscape. These locations will be compared to remotely-sensed imagery of snow distribution, aspect, and soil moisture providing important information regarding constraints of landscape-scale shrub distribution. This will allow us to characterize differences between shrub patches and the surrounding tundra environment, of which little is currently known.
- Transects were run through 10 alder patches and 10 open tundra locations adjacent to the patches. These patches were established along topographic gradients and paired open tundra measurement sites were established at each topographic position. Several biotic and abiotic measurements were made along these transects including plant community composition and structure, maximum thaw depth, soil moisture, organic layer depth, and canopy cover.
- To explore constraints on alder regeneration at the patch scale two experiments were carried out. First, alder seedling densities were determined across the topographic gradients using plotless sampling methods as well as quadrat counts. Second, experimental manipulations of abiotic conditions as well as seed availability will be employed in 2017 in order to expand this objective.
- 32 alder individuals were instrumented with heat ratio method sap flow sensors. At eight of the ten patches described above, we instrumented individuals at each of four positions: plateau, mid-slope, slope bottom and drainage channel. We have continuous sap flow data from early June to late August capturing the majority of the growing

season. We are currently measuring sapwood area on cookies from these shrub stems in order to facilitate upscaling of shrub water use to larger areas. Shrub water potential measurements were made across these same gradients in order to assess whether shrubs experience drought stress on any part of the landscape during the growing season. Finally, leaves from all of these shrubs were collected for nitrogen analysis to assess whether landscape position and water availability impacted plant nutrient availability. These data will all be analysed before the 2017 field season thereby guiding refinement questions surrounding water and nutrient constraints on shrub distribution.

Eddy covariance:

- In April 2013 we initiated eddy covariance measurements at the TVC watershed to continuously monitor water and energy exchanges between the land surface and the atmosphere and as required by our Arctic Net program, but also measure carbon fluxes required for our other studies at TVC.
- These measurements complement a series of radiometric (e.g., net radiation and its components) and environmental measurements (e.g., soil moisture and temperature) that started in 1991. Understanding these fluxes is a key component of understanding snow melt, soil moisture and ecological conditions across this rapidly evolving tundra landscape.
- In August 2016 we removed the old tower at TVC for safety and installed a new tower and reinstalled all the eddy covariance instrumentation.
- In May 2016 we installed a new eddy covariance system over a small lake in the TVC watershed in order to monitor evaporation from the lake from melt to freezeup. There were a few technical difficulties that limited data for periods of the summer, but these issues have been fixed for 2017.
- With funding from another source, we have hired a full time Research Associate to maintain the eddy covariance instrumentation at TVC (and other sites across the NWT).

Snow and soil moisture Remote Sensing:

- Soil and snow measurements from TVC contributed to the validation of the landscape freeze/thaw product derived from L-band radar measurements from the NASA Soil Moisture Active Passive (SMAP) mission.
- The beta release of the SMAP dataset occurred in October 2015, with the final validated release schedule for April 2016, following the failure of the SMAP.
- TVC is a core validation site for the NASA SMAP freeze/thaw product, providing a unique suite of soil and snow measurements in a shrub tundra environment.
- Radar in July 2016 for TVC were used to assess the capability to shift the freeze/thaw product to SMAP radiometer (passive) measurements.
- TVC represents an important site for ongoing analysis of radar interactions with terrestrial snow. Ongoing radar retrieval development (using experimental airborne data acquired in 2012/13) and recently initiated distributed hydrological simulations are core components of mission concept studies for new snow radar systems, underway at CSA and ESA.
- Meetings with NASA ABoVE, GNWT, and POLAR during 2016 and 2017 have confirmed that TVC is a key Canadian study site for the ABoVE airborne missions in 2017. TVC will provide key validation data for ABoVE, and ABoVE will provide key remote sensing information for understanding soil moisture, vegetation, and active layer variability over the TVC watershed and for testing and validating hydrological models.

RESULTS

The 2016 field season was extremely productive, and analysis of the data is proceeding. All our studies are on schedule. Key new findings and advances are outline below:

Spring air temperatures and start of snowmelt:

- Analysis of the 2016 data is ongoing in order to put this year into the long term context in terms of temperature and precipitation. Early analysis shows that the 2016 melt period was the earliest on record (Figure 2), and as a result the start of snowmelt was the second earliest on record (Figure 3).

Snow:

- End of winter Snow Water Equivalent was the lowest on record (Figure 4). This, when combined with an extremely early and rapid melt, resulted in an extremely unusual spring melt season, and one of the longest snow free summers on record. Full analysis of these data is waiting Water Survey of Canada to release the 2016 streamflow data.
- Images from an Unmanned Aerial System (UAS) when analyzed using structure-from-motion software, accurately mapped snow depth for Siksik Creek, and when combined with modelled snow density distribution, allows the mapping of SWE (Figure 5). This method has enormous implications for our understanding of snow distribution, and for providing the necessary data sets for testing snow models. Preliminary data suggest that earlier methods based on snow depth probing, greatly under estimate the range of snow depths across a watershed and show many more deep snow drifts than were observed by simple snow depth sampling.
- The UAS procedure was also used to map changes in snow covered area and SWE during the 2016 melt period (Figure 6).

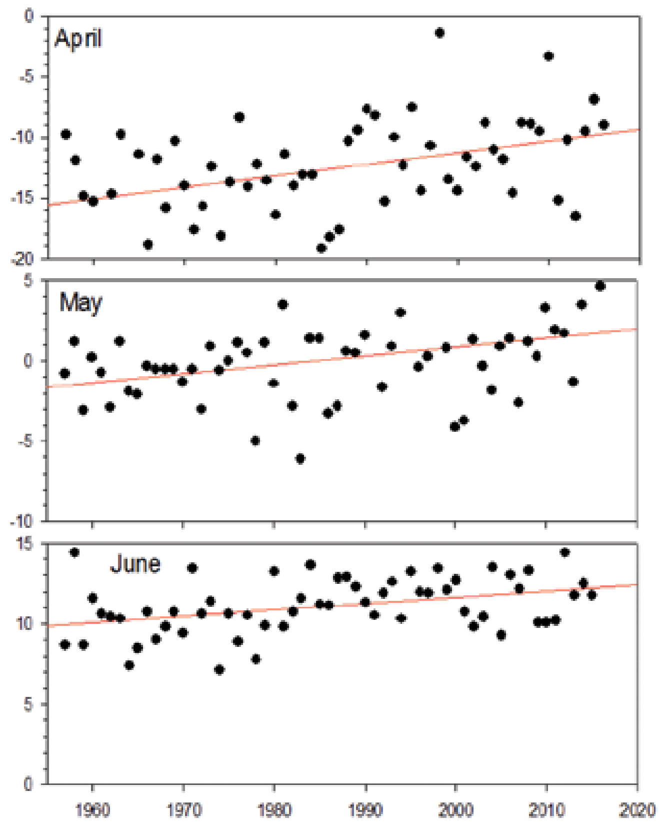

Figure 2. Temperature record for Trail Valley Creek. Note that May, the main snowmelt period, was the warmest on record.

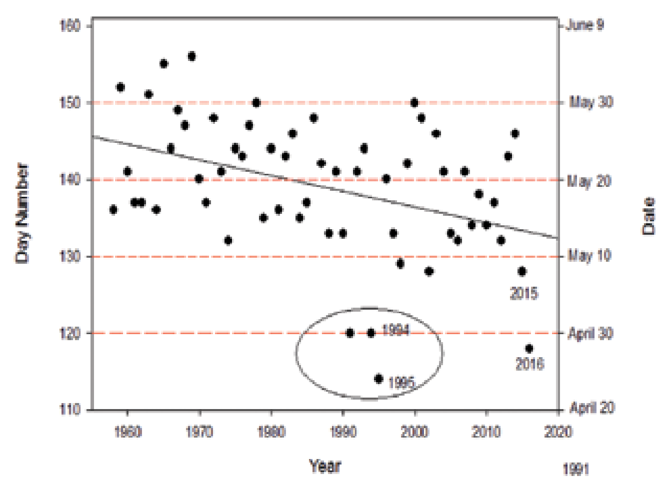

Figure 3. As a result of the warm spring air temperatures, the 2016 snowmelt was the second earliest on record.

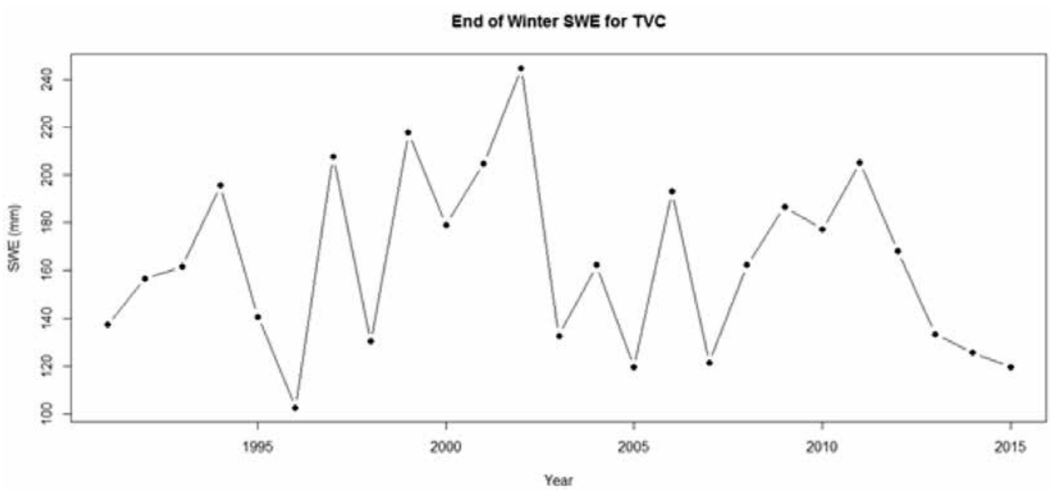

Figure 4. Snow surveys carried out at TVC since 1991 show that the 2016 end of winter snow water equivalent (SWE) (approximately 100 mm SWE, but not shown on this figure) was the lowest on record.

Soil Moisture:

- Significant progress towards soil moisture estimation in the arctic was made with recently graduated student Ms. Elizabeth Wrona. Ms. Wrona's thesis details soil moisture estimation using several approaches for the arctic. The thesis describes a method for the calculation of soil moisture using cosmic ray probes installed at the TVC meteorological stations. Unlike typical soil moisture observation, the cosmic ray instruments have an advantage in that the measurement area encompasses a large footprint (~200 m radius), relative to typical probes that represent a much smaller region. Much of the established literature defining the calibration of these devices is based on work at lower latitude in predominately mineral soils. Development of calibration equations for this environment required numerous observations of soil properties, soil moisture (using other approaches) and meteorological data. Results suggest that relatively strong relationship of between ancillary soil moisture observation with the cosmic ray probe (Figure 7). The data from the ancillary soil moisture stations (used for the calibration of cosmic ray probe

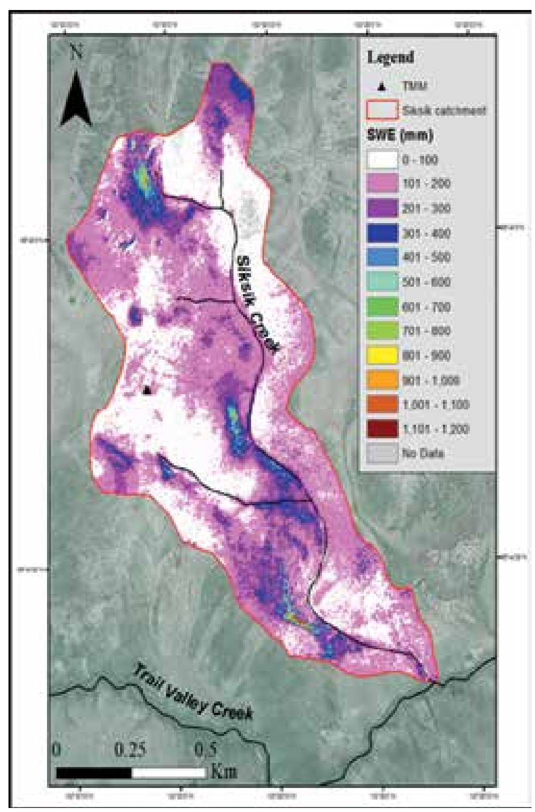

Figure 5. Map of end of winter snow water equivalent (SWE) derived from analyzed UAS images to map snow depth, and modelled snow density. This ability has not been demonstrated previously in the arctic.

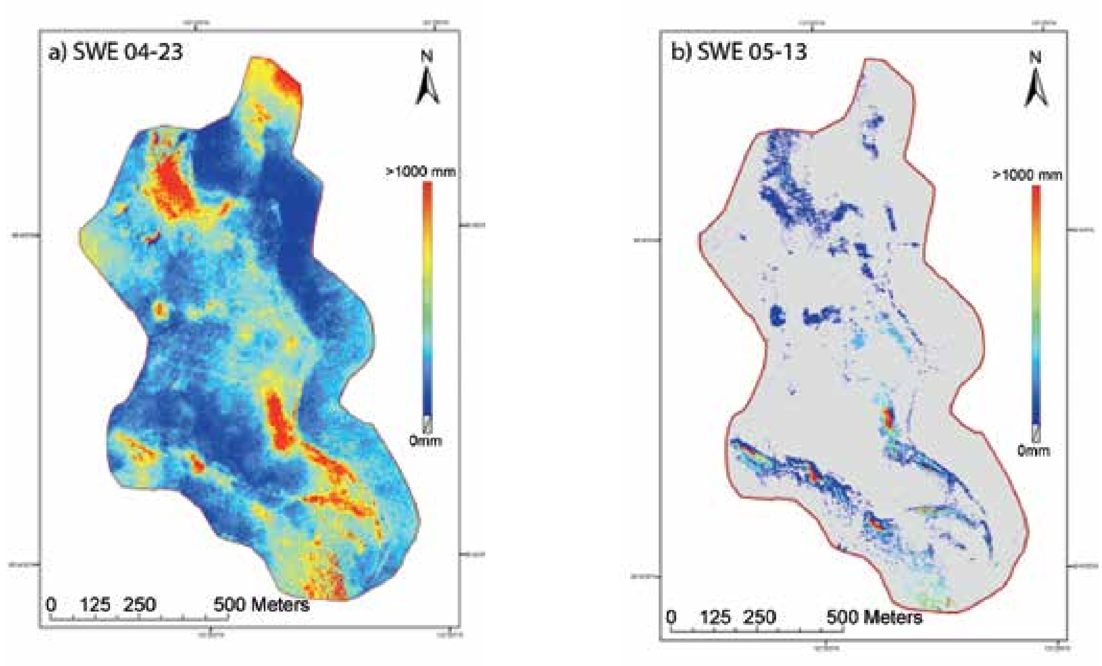

Figure 6. Mapping snow cover and SWE during the snowmelt period for a) April 23 2016 and b) May 13 2016.

were used in conjunction with data collected during weekly field visits to evaluation the applicability of soil moisture product recently released as part of NASA's Soil Moisture Active Passive (SMAP) mission. This data suggests that users must not use the direct SMAP NASA soil moisture product for soil moisture estimation for applications in the north. However, further evaluation of the satellite brightness temperatures (not the derived soil moisture products) suggest that a soil moisture product can be developed for the region. To improve the algorithms used to retrieve of soil moisture in tundra environments detailed study of the process was conducted over TVC area during August 2016. For this study an L-Band Radiometer (an instrument similar to that flown on the NASA SMAP and European Space Agency Soil Moisture and Ocean Salinity mission) was deployed at the TVC and operated continuously using a tower. This time series is currently being analyzed to further understand the ground parameters necessary to improve the satellite-based retrieval. ssues such as the organic soils and potentially interaction with permafrost need to be developed and considered for retrieval of soil moisture from these regions.

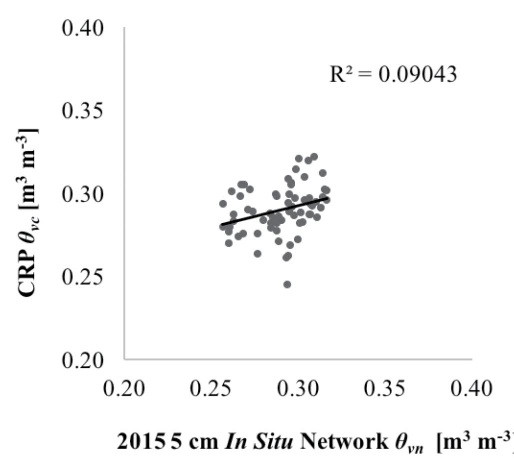

Figure 7. Relationship between measured soil moisture in the top 5 cm, vs that estimated for the cosmic ray probe for an area 200 m in radius around the probe.

Active Layer thickness:

Analysis of the extensive 2016 active layer surveys are being analyzed to quantify the spatial and temporal variability in frost depth and will provide important information on the development of water pathways controlling streamflow response. In addition, they will help with understanding the relationship between shrubs, topography, and active layer – a topic of considerable uncertainty and importance. Finally, these data will be a key data set for GEOtop validation. Preliminary analysis of these data show that end of summer active layer depths are much deeper than when similar surveys were completed in the mid-1990's. Analysis, and modelling, are ongoing to better understand these changes.

Shrub vegetation:

- Sap flow measurements from typical shrubs were carried out both 2015 and 2016. These data show that average daily cumulative sap volume, and indication of water use and shrub physiological function, was best explained by a combination of topgraphic position, soil moisture at 5 cm, and frost table depth. As shown in Figure 8, as seasonal thaw progressed, shrub function declined as the water table moved down with the frost table, effectively drying out surface soils towards the end of the growing season.
- A key factor in controlling shrub growth is nutrient availablility, using PRS probes (Figure 9) suggests greater nutrient availability in shrub patches compared to surrounding tundra.

Eddy covariance:

- 2016 eddy covariance and supporting measurements were carried out at a tundra site in Siksik Creek, and from a small lake in the vicinity. This will allow the comparison of turbulent fluxes of latent and sensible heat between tundra and lakes in the TVC watershed north of the treeline to those over a forest canopy at Havikpak Creek watershed south of treeline.

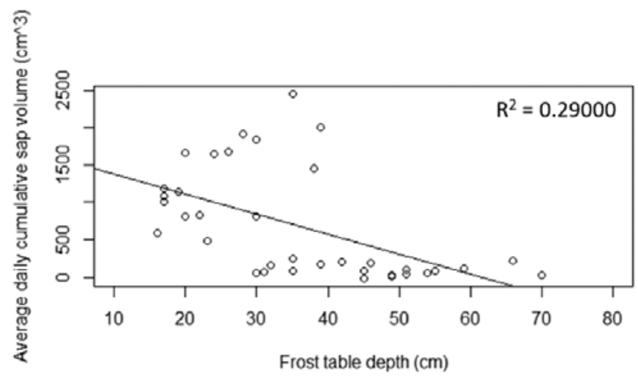

Figure 8. The summary of the candidate generalized linear mixed effects model with the most support predicting average daily cumulative sap volume of 27 green alder shrubs from early June to late August in 2015 indicated that frost table depth was a significant predictor of shrub physiological function. The relationship between frost table depth and average daily cumulative sap volume demonstrated that as seasonal thaw progressed, shrub function declined as the water table moved down with the frost table, effectively drying out surface soils towards the end of the growing season. In 2016, this relationship was similar, but weaker, potentially because of higher rainfall during the 2016 growing season (less moisture stress).

- Eddy covariance estimates from TVC and other sites across the NWT were used to suggest changes instrumentation to the manufacturer. These changes are being applied, and will be part of standard procedures for all users in the future.

Snow Remote Sensing:

- Time series of descending overpass SMAP L-band radar backscatter and radiometer normalized polarization ratio (NPR) along with coincident soil and air temperature measurements for TVC during spring 2016. There is clear L-band response (both active and passive) to freeze/thaw transitions, with evidence that the radar and radiometer FT flags are responding to the onset of wet snow, as indicated by transient early season thaw events when air temperatures exceeded zero (hence inducing snow melt) but soil temperatures remained below zero. These events are more

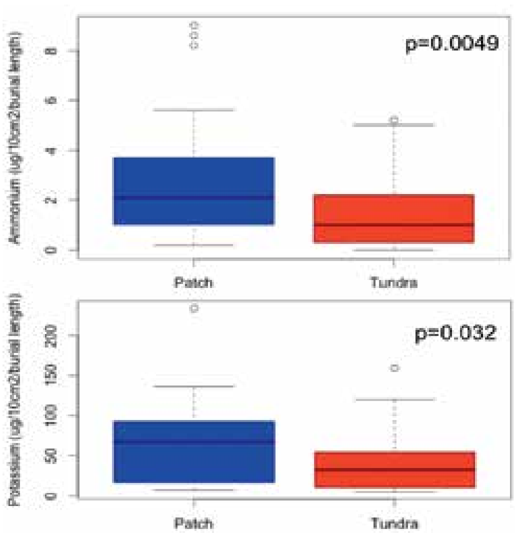

Figure 9. Ammonium (top) and potassium (bottom) values from PRS probes installed along ten paired alder patch and alder-free ('open tundra') transects. Quantities of both nutrients are significantly greater in alder patches, suggesting greater nutrient availability in patches compared to the surrounding tundra.

frequent with the ascending overpasses due to warmer afternoon temperatures (not shown). The ongoing measurements at TVC are making an important contribution to SMAP freeze/thaw validation, which in turn supports the use of SMAP products for ecological and hydrological applications across Canada.

Modelling

- SnowModel runs are ongoing, and Dr. Toure has been working with Dr. Liston (Colorado State University) to improve the model. Currently SnowModel is able to predict the distribution of SWE across the basin with reasonable accuracy (Figure 10). Currently the model underestimates the SWE in drifts, likely due to the model not being designed to run with grid squares of less than 20 m. When using such grid sizes, the model underestimates the impact of shrub patches or hill slopes on the wind flow pattern. We are working with Dr. Liston to incorporate an existing, and published, routine to allow the use of finer grid

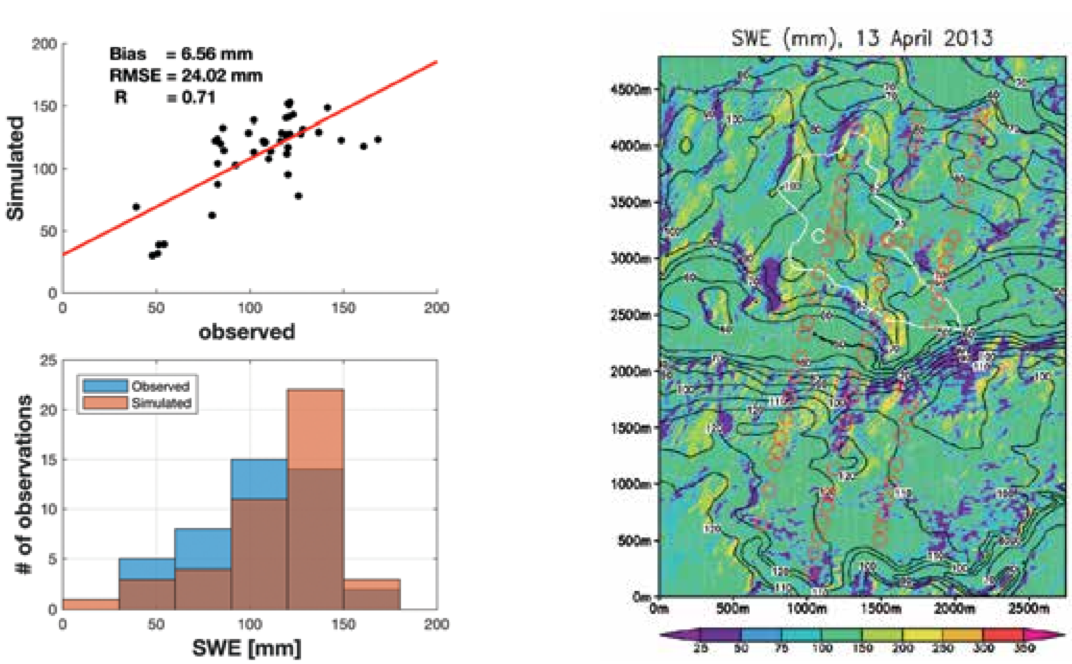

Figure 10. Comparison of observed SWE vs simulated using SnowModel for an extensive observation period in April 2013. In the coming year we expect to improve the simulations of deep snow drifts, and to compare these to the data sets from 2015 and 2016.

sizes. This is expected to improve the model estimates of snow drift sizes, a key requirement for considering the impact of shrub patches on snow, and permafrost, and runoff.

DISCUSSION

Our second field season was extremely successful, and preliminary data analysis and modelling is showing that we are on track to answer the key questions raised by this project. This is namely, can we improve our understanding of the interaction between key aspects of the terrestrial environment, namely the complex interactions between climate, snow, active layer, soil moisture, shrubs, and streamflow. Understanding these complex interactions, and testing, improving and validating predictive models are key to understanding past changes to this system, and considering future changes as the climate continues to dry, and the precipitation changes (precipitation has decreased over the last 60 years in this region, but is forecast to increase in the coming decades.

CONCLUSION

To date we have made tremendous progress, and are on track to meet all of our objectives. Our field work, with staff and students on site at Trail Valley Creek (a total of approximately 500 person days), was extremely successful. We have verified the utility of several new instruments, including Cosmic Ray Sensors and an Unmanned Aerial System, and improved eddy covariance measurements. These have greatly enhanced our ability to measure snow cover and soil moisture. We have also made significant advances in mapping shrubs and in measuring sap flow. Although we had significant instrument issues with our eddy covariance system in the summer of 2016, these have been repaired and the system is working and we are expanding our multiple year data set. Metadata on key aspects of our data collection have been input to the Polar Data Catalogue, and we are continuing to add additional metadata. Our Post-Doctoral Fellow, Dr. Ally Toure has made significant progress in testing and improving a snow model for use in considering the interactions between snow and shrub patches.

ACKNOWLEDGEMENTS

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COUPLED TERRESTRIAL-AQUATIC CLIMATE IMPACTS ON HIGH ARCTIC WATERSHEDS: USING THE LAKE HAZEN WATERSHED AS A SENTINEL FOR CHANGE

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ABSTRACT

A whole-ecosystem study is being conducted to quantify coupled terrestrial-aquatic impacts of climate change on high Arctic watersheds, using the Lake Hazen watershed in Quttinirpaaq National Park on northern Ellesmere Island, Nunavut, as a sentinel system. To accomplish this goal, the following are being quantified: 1) net exchange of energy, H_2O, CO_2 and CH_4 between the atmosphere and terrestrial landscapes in the watershed; 2) net mass change of glaciers in the watershed; 3) chemical inputs to Lake Hazen from snowmelt, glacier melt and soil/permafrost thaw; 4) the metabolism of Lake Hazen itself; and 5) long-term biological and biogeochemical changes in Lake Hazen and its watershed using sediment cores. Emphasis is being placed on understanding: 1) sources, quality and age of the organic carbon (OC) and nutrients entering Lake Hazen; 2) 'hot spots' where major biogeochemical processes altering OC and nutrients occur; and 3) the rates at which these biogeochemical processes are evolving. Identification of sources, and quantification of inputs, of legacy contaminants (e.g., mercury, persistent organic pollutants) is being undertaken through a partnership with Aboriginal Affairs and Northern Development Canada and their Northern Contaminants Program. From an applied and socio-economic perspective, increasing our ability to predict impacts of warming northern ecosystems on watershed productivity and water quality is vital for securing food, clean drinking water and traditional lifestyles for Northern peoples.

KEY MESSAGES

- We identified four types of biogeochemically distinct freshwater systems in the Lake Hazen watershed.
- Atmospheric exchange of carbon dioxide (CO_2) was similar and low between these systems, whereas seasonal flooding of ponds bordering Lake Hazen generated considerable methane (CH_4) emissions to the atmosphere.
- Freshwaters were unimportant contributors to total watershed CO_2 and CH_4 exchange, in part because they covered less than 10% of total area in the watershed.
- Concentrations of CO_2 in the glacial rivers were below atmospheric equilibrium throughout the watershed and in shallow waters near the shoreline of Lake Hazen because of geochemical weathering of carbonate and silicate minerals. CO_2 concentrations decreased with increasing distance from glacier termini, indicating active weathering of recently comminuted, geochemically active sediments.
- Climate change is greatly enhancing glacial melt in the Lake Hazen watershed, where surface temperatures of glaciers have been increasing up to 0.15^{o}C per year since 2000.
- Increased glacial runoff has changed the water residence time of Lake Hazen, resulting in a decreased lag between chemical inputs to the lake from glacial rivers and Lake Hazen water chemistry, but Lake Hazen still not being at steady state with respect to its inputs.
- With regards to nutrients, concentrations of nitrite+nitrate (NO_2+NO_3) were similar in glacial river inputs to Lake Hazen, throughout the water column of Lake Hazen, and at the Ruggles river outflow of Lake Hazen, whereas concentrations of total phosphorus (TP) were much higher in glacial river inputs than throughout the water column of Lake Hazen, and at the Ruggles river outflow, suggesting that a large portion of the TP entering the lake settles out on particles.
- Concentrations of some nutrients (TP, total nitrogen [TN], particulate carbon/nitrogen [PC, PN]), methylmercury (MeHg) and total mercury (THg) in two frequently sampled glacial rivers (Snowgoose River and Blister Creek) increased with increasing flow intensity, suggesting that erosional materials are the source of the nutrients and Hg.

- Dissolved organic matter (DOM) and concentrations of dissolved organic carbon (DOC) in Lake Hazen reflected 'glacial' signatures.
- 'Glacial' signatures of DOM sampled from glacial rivers differ from 'terrigenous' signatures taken from overland soil/permafrost seep sites and the Skeleton Lake subcatchment that is hydrologically driven by permafrost thaw.
- With regards to contaminants, concentrations of MeHg and perfluorinated alkyl substances (PFASs) at the Ruggles River outflow were lower than any of the inflow concentrations, suggesting that a combination of sedimentation, dilution and photodemethylation is occurring in the lake.
- Concentrations of predominately particulate-bound MeHg/THg in the Ruggles River increased with increasing distance from Lake Hazen towards Chandler Fjord, as a result of erosion and permafrost slumping.
- NO_2+NO_3 coming out of a soil/permafrost thaw seep was quickly used up downstream in hydrologically connected Skeleton Lake, ponds and wetlands, suggesting that these types of sub-catchments in the Lake Hazen watershed are very N-limited, and rely on efficient recycling of organic nitrogen.
- MeHg concentrations increased as water moved through Skeleton Lake and two downstream ponds, indicating that these were both sites of active microbial Hg methylation.
- Small soil/permafrost thaw streams appeared to be localized productive zones, contributing higher concentrations of DOC to surrounding creeks and rivers.
- As in summer 2015, the Lake Hazen water column mixed completely in 2016: dense turbid glacial rivers form underflows upon entering the lake, transporting oxygenated waters, but also particulate matter, to the bottom of the lake.
- δ^{15}N signatures on particulate organic matter (POM) from Lake Hazen suggest that Lake Hazen may be N limited.
- Dissolved O_2 was depleted within the top centimeter of Lake Hazen sediments collected in summer 2016, regardless of the depth from which sediments were collected, suggesting very active microbial respiration in sediments even under oxygenated water column conditions. Sequences assigned to chemoheterotrophic microbes also dominate in the top sediments collected in 2014 and 2015 in Lake Hazen.
- The microbial diversity of Skeleton Lake sediments seems to be lower than in Lake Hazen sediments, and the inferred functionality of the Skeleton Lake community is very dissimilar to Lake Hazen. The sediment microbial communities in Lake Hazen are also very heterogeneous, probably owing to unique physiochemical characteristics of the three sampling sites.
- The differences between the taxonomic compositions of the sediment microbial communities seem to be driven by gradients of H_2S, pH, and redox potential. In addition, water depth seems to contribute to the community composition as a proxy of light availability and nutrient availability through differing particle settling dynamics.
- Microbial DNA has been successfully isolated from glacial rivers, Skeleton Creek and Lake Hazen waters.

OBJECTIVES

To examine coupled terrestrial-aquatic impacts of climate change on high Arctic watersheds, our research has five specific objectives. We are quantifying:

1. net exchange of energy, water, CO_2 and CH_4 between the atmosphere and terrestrial landscapes in the Lake Hazen watershed;
2. net mass change of glaciers in the Lake Hazen watershed;

3. chemical inputs to Lake Hazen from snowmelt, glacier melt and soil/permafrost thaw;
4. the metabolism of Lake Hazen itself; and
5. long-term biological and biogeochemical changes in Lake Hazen and its watershed using sediment cores.

Emphasis is being placed on understanding:

1. sources, quality and age of the organic carbon (OC) and associated nutrients entering Lake Hazen;
2. where major biogeochemical processes altering OC and nutrients occur (i.e., hot spots); and
3. the rates at which these biogeochemical processes are evolving.

We are also identifying sources, and quantify inputs, of legacy contaminants (e.g., mercury (Hg), perfluorinated alkyl acids, organophosphorus flame-retardants) through a collaborative partnership with Indigenous and Northern Affairs Canada (INAC) and their Northern Contaminants Program (NCP).

KNOWLEDGE MOBILIZATION

- Nine presentations at scientific conferences;
- One published and one submitted peer-reviewed papers;
- Translation of our Parks Canada research permits and reports into Inuktitut for distribution to the Quttinirpaaq National Park Joint Parks Management Board and Northern Community Members;
- On-site (Lake Hazen) bi-directional knowledge transfer between Parks Canada employees (some of whom are Northern residents) and scientists/students;
- Development of an interactive Lake Hazen website (www.lakehazen.ca);
- Continued production of short scientific outreach documentary that will be readily distributed to interested communities and agencies (e.g., Indigenous and Northern Affairs Canada, Parks Canada) and posted on our website.

INTRODUCTION

Human-induced climate change is altering polar watersheds at unprecedented rates [1, 2]. Climate models predict that, given current rates of greenhouse gas (GHG) emissions, autumn and winter temperatures and precipitation are projected to rise by 8.3°C and 40%, respectively, in the very northern Canadian Arctic Archipelago by 2100 [3]. Such warming and wetting, coupled with extended growing seasons [4], is anticipated to greatly alter the energy balance of Arctic landscapes [5], resulting in increased glacial melt [6], permafrost thaw [7], altered surface runoff regimes [8], and increased net primary production (NPP) in watersheds [9] and freshwaters [10]. In fact, most of these changes are already occurring in the Lake Hazen watershed, located within Quttinirpaaq National Park, northern Ellesmere Island, Nunavut. Lake Hazen is globally the largest Arctic lake by volume (surface area 540 km^2, maximum depth 265 m, and a catchment area of 6860 km^2, half of which is glaciated) [11], and supports one of the largest stocks of landlocked Arctic char (*Salvelinus alpinus*), historically harvested by various arctic-adapted cultures, including the modern Inuit. Over the past decade, satellite imaging revealed a decline in Lake Hazen ice cover duration [12], and summer mean glacier surface temperatures up to 1.25°C warmer than the previous decade. This resulted in ~10-fold increases in glacial runoff into Lake Hazen, mirrored by a 10-fold increase in sedimentation rates.

Despite these recent and significant physical changes in the watershed, it is unknown how, and on what timescale, the increased inputs from the terrestrial system will change the productivity and health of Lake Hazen, a freshwater jewel of Canada's high Arctic. For example, although it is deep, cold, ultra-oligotrophic, and ice-covered for a large portion of the year, Lake Hazen is still biologically quite active. Recent late-

May under-ice profiles showed high concentrations of chl *a* and dissolved O_2 in the upper reaches of the water column, suggesting a spring pulse of NPP, likely important for jump-starting energy flow through the Lake Hazen food web following the long Arctic winter. However, O_2 decreased, and NO_3^- and CO_2 increased, in the bottom 50 m of the water column, suggesting substantial microbial activity in the underlying lake sediments. Will increased watershed inputs due to climate change dramatically change NPP in surface waters and microbial activity in lake sediments? Will these changes be reflected in other freshwater systems in the watershed (smaller lakes, pond, wetlands) and across the high Arctic?

We proposed a whole-ecosystem study to quantify coupled terrestrial-aquatic impacts of climate change on high Arctic watersheds, using the Lake Hazen watershed as a *sentinel system*. Specifically, we are determining how physical and biogeochemical processes are changing on the landscape, and exploring how these landscape changes are impacting biogeochemical processes and water quality in the lake itself. *Using the Lake Hazen watershed as a sentinel system is ideal because it*: 1) has a hydrologically-gauged outflow (Ruggles River) that can be compared with measured/modeled water volumes produced by precipitation, melt/thaw of snow, glacier ice and permafrost in the catchment; 2) has historic data from previous intermittent research programs from which we can build long-term datasets; 3) is located in a pristine National Park, thus recording climate and other changes in isolation of direct and confounding disturbances; and 4) encompasses many different environments (glaciers, tundra, wetlands, lakes), from which to compare and integrate all in a single watershed. This last point is particularly important because it will allow us to extrapolate our findings to other Arctic watersheds using the mechanistic understanding obtained in this study of how different watershed components respond to a changing climate, thus improving our predictive ability to understand the future of all Arctic freshwater ecosystems and their valuable goods and services. Further, this is one of the very few places in the high Arctic where the supply of nutrients from the terrestrial catchment to the near-shore coastal marine system can be studied.

ACTIVITIES

Fieldwork was carried out from 28 June to 8 August 2016 at Lake Hazen. During this time in the field, as well as outside the field season, we concentrated on the first four objectives of our research program. Objective 5 will be addressed in 2017/18.

1) Net exchange of energy, water, CO_2 and CH_4 between the atmosphere and terrestrial landscapes in the Lake Hazen watershed (now revised to focus on the net exchange of CO_2 and CH_4 between the atmosphere and aquatic ecosystems in the Lake Hazen watershed):

- Datasets relating to the original goals of this objective were previously published in: Emmerton, C.A., V.L. St.Louis, E.R. Humphreys, J.A. Gamon, J.D. Barker and G.Z. Gilberto. 2015. Net ecosystem exchange of CO_2 with rapidly changing high Arctic landscapes. Global Change Biol. doi: 10.1111/gcb.13064 (Emmerton, St.Louis).
- Early datasets on the revised goals of this objective, compiled between 2005-2012, were published during this past fiscal year in: Emmerton, C.A., V.L. St. Louis, I. Lehnherr, J.A. Graydon, J.L. Kirk, K.J. Rondeau. 2016. The importance of freshwater systems to the net atmospheric exchange of carbon dioxide and methane with a rapidly changing high Arctic watershed. Biogeosci., 13:5849-5863. (Emmerton, St.Louis, Lehnherr).
- During summer 2016, we completed comprehensive spatial and temporal surveys of the glacial rivers, as described in Objective 3, to determine whether the rivers are CO_2/CH_4 sources or sinks to the atmosphere (St.Pierre, St.Louis, Aukes, Dainard, Schiff, Lehnherr, Serbu).

2) Net mass change of glaciers in the Lake Hazen watershed:

- In August 2016, we installed high precision GPS units near the margins of the Henrietta Nesmith (N81.83562° W73.21759°) and Gilman (N82.15442° W70.76949°) glaciers to collect year-round (every 30 seconds) measurement of the elevation of bedrock surfaces. These measurements document the elastic deformation of the crust in response to changes in glacier mass loading in the Lake Hazen watershed, and can be used to compute the magnitude of both annual and seasonal (summer/winter) changes in glacier mass (Danielson, Dubnick).
- In addition, we completed field reconnaissance for potential sites for installation of two additional GPS systems in 2017. One would be located on a nunatak within the northern Ellesmere Icefield and the other near the Ruggles River. We have begun to build the two additional GPS units that will be deployed in 2017 (Danielson, Dubnick, Sharp).
- We completed our analyses of the MODIS Land Surface Temperature (LST) record for all glaciers on Ellesmere, Devon and Axel Heiberg islands (Mortimer, C.A., M. Sharp and B. Wouters. 2016. Glacier surface temperatures in the Canadian High Arctic, 2000-15. *J. Glaciol.* 62: 963-975), and of changes in the thickness of the northern Ellesmere Island glaciers using data from repeat airborne laser altimetry missions flown over the region by NASA in 1995, 2000, 2005/06 and 2012/14 (Mortimer, Sharp).

3) Chemical inputs to Lake Hazen from snowmelt, glacier melt and soil/permafrost thaw:

- Snow was not collected in 2016 as no spring fieldwork was completed. Snow will again be collected in 2017.
- We are extremely fortunate at Lake Hazen because the Skeleton Lake subcatchment allows us to quantify how soil/permafrost thaw water quality changes as it moves from: 1) distinct seepage sites; 2) through Skeleton Lake; 3) two smaller ponds; 4) *Carex* grass dominated wetlands; and 5) a tundra creek channel, prior to discharging into Lake Hazen. At these strategic sites, samples were taken every ~7 days for analyses of nutrients and other chemical parameters (dissolved N, particulate N, NO_3^- /NO_2^-, NH_4^+, total P, total dissolved P, dissolved inorganic C [DIC], DOC, total dissolved solids, Cl^-, SO_4^{2-}, major cations/ metals) and contaminants (MeHg, THg). To map evaporation, water sources and the evolution of water quality, samples were collected for $\delta^{18}O$, δ^2H-H_2O, SO_4^{2-}, and $\delta^{34}S$- SO_4^{2-} over the season from the Skeleton Lake subcatchment. Specific attention was paid to the quality and quantity of dissolved OC throughout the subcatchment, as well as over the summer season. DOC was characterized using a suite of techniques, including size-exclusion chromatography, elemental ratios, ultra-violet and visible absorbance, fluorescence scans, and $\delta^{13}C$-DOC. Finally, isotopes ($\delta^{13}C$-DIC and $\delta^{18}O$-O_2) were collected from a series of ponds and Skeleton Lake to look at in-lake and pond productivity over the summer. Previous work identified differences in hydrology (evaporative versus flow-through ponds), allowing us to compare changes in geochemistry and DOC among hydrologically-different ponds (Lehnherr, Wisniewski, Schiff, St.Pierre, Aukes, Dainard, Cavaco, Serbu, St.Louis).
- Metabolism in Skeleton Lake itself was assessed during the open water season by quantifying net primary productivity (NPP) of surface waters, lake respiration, and air-water CO_2 exchange. A YSI EXO2 sonde with dissolved O_2, pH, conductivity, temperature and total algae sensors was deployed from 6-21 July to obtain a continual record of these parameters during ice-free conditions in surface waters of Skeleton Lake. Profiles of these parameters, along with photosynthetically active radiation (PAR), were

also measured throughout the watercolumn on July 6, 9, 13, 17, and 21 to provide measures of thermal stratification, zones of productivity, etc. during the open water season. A chain of HOBO temperature loggers continuously recorded water temperature at discrete depths to further resolve thermal stratification. Concentrations of CO_2 in surface waters were measured using a Vaisala CO_2 sensor to calculate net fluxes to the atmosphere. A raft equipped with meteorological instrumentation (anemometer, and PAR, air temperature and barometric pressure sensors) was also deployed on Skeleton Lake (Lehnherr, Wisniewski).

- Rates of Hg methylation and demethylation were quantified at numerous sites and times along the Skeleton Lake subcatchment, using stable Hg isotope incubation experiments, to determine hotspots of net MeHg production on Arctic landscapes (Lehnherr, Wisniewski, Varty).
- In depth sampling along the ~11 km Blister Creek continuum was performed during two hikes on 15 and 29 July. Samples encompassed water from its glacial source, from several small streams and overland seepage sites that flow into Blister Creek, and at the point where Blister Creek discharges into Lake Hazen. The sampling design allowed us to assess whether there were appreciable changes along the length of Blister Creek to DOM quantity and quality, DOM absorbance and fluorescence properties, concentration of DOC and nutrients, with stable C isotope measurements ($\delta^{13}C$) being of particular interest. The age and source of glacial river C will be obtained from samples taken for ^{14}C-DOC and ^{14}C-DIC analyses (Aukes, Dainard, Schiff).
- Twice in 2016 (July 11-13 and August 1-2) we accessed five of the ungauged glacial inflow rivers (Abbé, Gilman, Henrietta Nesmith, Very, Turnabout) as well as the outflow Ruggles River, by helicopter to sample for general water chemistry. In July, this was done in cooperation with Parks Canada and Environment and Climate Change Canada, who concurrently sampled four of the rivers (not Gilman or Henrietta Nesmith) as part of their annual water quality survey. During these surveys, we also conducted transects along the Snowgoose, Gilman and Ruggles Rivers to assess changes in water chemistry over space (St.Louis, Lehnherr, Talbot, St.Pierre, Aukes, Dainard, Cavaco, Wisniewski, Serbu).
- There are two ungauged glacially-fed rivers within walking distance of the Lake Hazen base camp that we used to examine seasonal patterns in glacial runoff chemistry and loadings. Blister Creek and the Snowgoose River are representative of smaller and larger inflow rivers, respectively. We sampled these two rivers at their mouths every ~7 days from late June to early August to relate seasonal changes in glacial discharge with chemical inputs to Lake Hazen (St.Louis, Lehnherr, St.Pierre, Aukes, Dainard, Cavaco, Serbu).
- A shoreline transect of Lake Hazen, spanning the distance between Blister Creek and the Snowgoose River, was sampled twice on 23 and 30 July. This sampling plan was designed to probe whether there were point source contributions of carbon (i.e., DIC, DOC) to Lake Hazen from soil slumping/erosion, discharge from small streams, or groundwater permeation from proximal ponds. Because significant lake ice melt was expected to occur in Lake Hazen during the week between sampling hikes, water isotopes ($\delta^{18}O$, $\delta^{2}H$-H_2O) were also sampled to determine water inputs from the ice itself (Aukes, Dainard, Schiff).
- At all major sampling sites throughout the field season, samples were collected and processed to identify which microbial guilds are present throughout the watershed as a complement to the extensive chemical dataset being compiled (Cavaco, St.Louis, St.Pierre).
- We also sampled for ^{3}H in all glacial rivers, Lake Hazen and the Skeleton Lake subcatchment to constrain the age and potential source of water in Lake Hazen (Aukes, Dainard, Schiff).

- We will estimate the contributions of each of the 16 input rivers to the hydrologically-gauged Ruggles River discharge outflow volume (measured by **Water Survey Canada**), on the basis of the drainage area of each input river subcatchment and the modeled glacial mass loss within it (Gardner, English, Sharp). In addition, Lake Hazen was instrumented with a pressure transducer from 25 June to 1 August to monitor lake level.

4) The metabolism of Lake Hazen itself:

- *Water column chemistry (including contaminants):* We measured freshwater quality in Lake Hazen to corroborate with our results from 2015 by conducting a water column profile at the deepest point of the lake (265 m) on 8-August. We first deployed a YSI EXO2 sonde with dissolved O_2, pH, conductivity, temperature and total algae sensors to confirm that the water column was mixed. Due to sustained inclement conditions on the lake following ice-out, we were unable to complete a full 15-depth profile as done in the past, but instead selected our sampling depths based on the sonde profile, strategically selecting depths of interest from the sonde. We sampled water using a cleaned 12 L Niskin bottle at the surface, 15 m, and 250 m for the complete suite of water chemistry as described above for river chemistry, including dissolved greenhouse gases and contaminants (St.Louis, Talbot, St.Pierre, Cavaco, Serbu).
- *Sediment microbial processes and diversity:* We used UNISENSE microelectrodes (O_2, H_2S, N_2O, pH and redox) to examine microprofiles of redox-related biogeochemical processes in sediment cores collected from 50 m and 265 m depths of Lake Hazen following ice-out in August. Companion cores were sectioned at 1-cm intervals for pore water (NO_3^- /NO_2^-, NH_4^+, total dissolved P, SO_4^{2-}), and solid (N, P, C and metals) analyses. DNA was isolated from a further companion core to characterize microbial communities by targeting ribosomal small subunit genes (16SrRNA) and key processes in nutrient and contaminant cycling (such as *mer*-operon genes) with PCR and NGS sequencing. These samples will be used also to quantify [THg] profiles in the sediment and sediment accumulation rates through ^{210}Pb dating. (St. Pierre, Poulain, Ruuskanen, Colby).

RESULTS

Below we highlight some of our major findings to date. However, analyses are still being completed for some of our activities, and results are not yet available.

1) Net exchange of energy, water, CO_2 and CH_4 between the atmosphere and terrestrial landscapes in the Lake Hazen watershed (now revised to focus on the net exchange of CO_2 and CH_4 between the atmosphere and aquatic ecosystems in the Lake Hazen watershed):

During the summers of 2005-2012, we quantified CO_2 and CH_4 concentrations in, and atmospheric exchange with, common freshwater systems in the watershed of Lake Hazen. This past year, we published a study showing that there are four types of biogeochemically-distinct freshwater systems in the watershed; however mean CO_2 concentrations and atmospheric exchange were similar between these systems. Seasonal flooding of ponds bordering Lake Hazen generated considerable CH_4 emissions to the atmosphere, while all other freshwater systems were minimal emitters of this gas (Emmerton, St.Louis).

Glacial rivers were increasingly under-saturated with respect to CO_2 throughout the summer as discharge increased, suggesting increasing geochemical weathering intensity with increasing melt during the summer months. Decreases in dissolved CO_2 over space were mirrored by increases in dissolved chemical constituents that are indicators of active geochemical weathering (Figure 1). As these chronically under-saturated rivers flow into Lake Hazen, the lake waters themselves become undersaturated in CO_2, albeit less so than the rivers due to dilution of the turbid river water by the clear lake water (St. Louis, St. Pierre).

2) Net mass change of glaciers in the Lake Hazen watershed:

The Henrietta Nesmith and Gilman Glacier GPS units are now collecting data (Figure 2). We also determined how to process the GPS data that is being collected in the Lake Hazen watershed with data from a station at Devon Ice Cap - which proved that the method works and we will be able to monitor seasonal variation in vertical motion of bedrock elated to glacier accumulation/ablation (Sharp, Danielson).

Surface temperatures of glaciers in the Lake Hazen watershed have been increasing up to 0.15°C per year from 2000-2015. Glacier thinning was widespread during this period, especially between 2005/06 and 2012/14. Both changes in glacier mass balance and, for some glaciers, changes in ice dynamics contributed to this thinning. In general, however, thinning coincided with rising ice surface temperatures (recorded by MODIS Land Surface Temperature data). It seems likely that a decrease in glacier surface albedo also contributed to accelerated rates of ice cap thinning (as is the case elsewhere on Ellesmere Island), but this cannot be confirmed due to a problem with the MODIS albedo data north of 80 degrees North (Sharp, Mortimer).

Melt discharge modelling results have not yet been completed (Sharp, Gardner), whereas the gauged Ruggles River discharge outflow volume measurements are still being quality controlled by **Water Survey Canada**.

3) Chemical inputs to Lake Hazen from snowmelt, glacier melt and soil/permafrost thaw:

Our chemistry results show much the same trends as they did in summer 2015. Average concentrations of NO_2+NO_3 ranged between 14 ug/L at the Gilman Glacier to 143 ug/L in Blister Creek. Average concentrations of TP ranged between 2 ug/L in the Snowgoose River to 1,840 ug/L in the Gilman River. The average concentration of DOC from glacial rivers was typically less than 1 mg/L. Concentrations of SO_4^{2-} varied among the inputs into Lake Hazen. Glacial rivers (~9 mg/L) were comparable to those in Lake Hazen (St.Louis, St.Pierre).

We found that average unfiltered MeHg concentrations ranged from 0.007 ng/L at the start of the summer in Blister Creek to 0.115 ng/L at peak flow in the Snowgoose River. Filtered MeHg concentrations were much lower and fairly consistent among the different rivers (0.007-0.021 ng/L), suggesting that a significant portion of the MeHg in glacial runoff is particle-bound. Both unfiltered and filtered concentrations of MeHg at the outflow of Lake Hazen in the Ruggles River were lower than any of the inflow concentrations. MeHg in the Ruggles increased (0.007 ng/L to 0.065 ng/L at the inflow to Chandler Fjord) with increasing distance from Lake Hazen due to an influx of particulate from bank erosion and small permafrost slumps (St.Louis, St.Pierre).

Because they were within walking distance of the Lake Hazen base camp, we were also able to sample the Snowgoose River and Blister Creek six times during the summer of 2016 to examine changes in contaminant concentrations with changing river flows. Average concentrations of NO_2+NO_3 varied little in the Snowgoose River and Blister Creek even though flow changed throughout the summer sampling season. Average concentrations of TP in both rivers did change with flow, however, from below detection to 1,260 ug/L in the Snowgoose River, and from below detection to 1,170 ug/L in Blister Creek, between periods of low and high flow. No trend was seen in DOC concentration over time from Blister Creek (St.Louis, St.Pierre).

Thus far, DOC concentrations along the Blister Creek continuum did not follow a pronounced trend, although lower DOC concentrations were generally found at the 'top' of Blister Creek proximal to the glacier melt water flow. DOM sampled from seepage

Figure 1. Ph.D. students Kyra St.Pierre and Pieter Aukes sampling a glacial river for concentrations of CO_2, CH_4 and dissolved inorganic carbon, among other parameters (Credit: V. St.Louis).

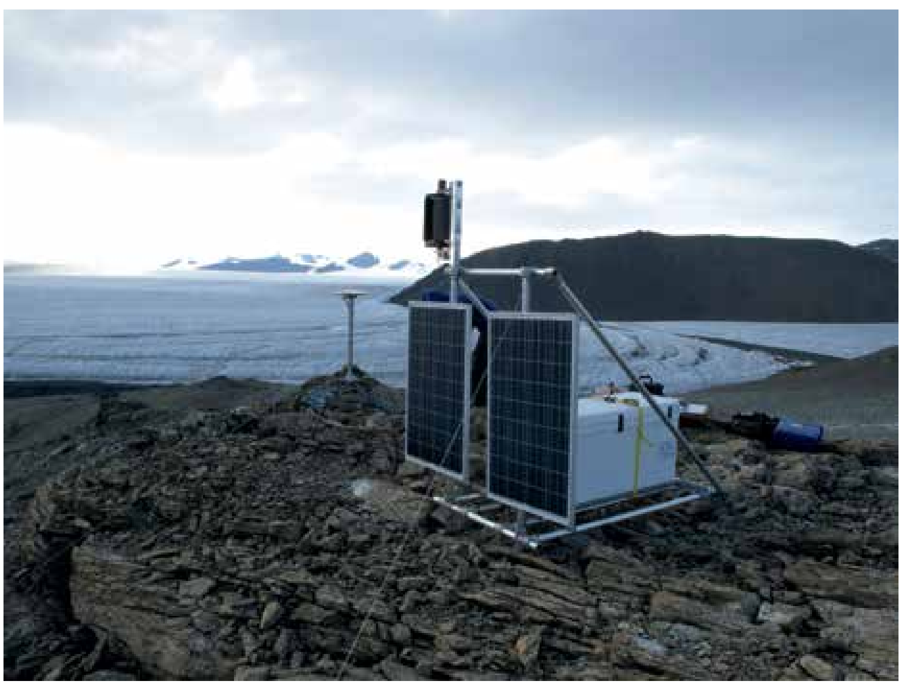

Figure 2. GPS unit installed on a rock outcrop along the edge of the Gilman Glacier (Credit: A. Dubnick).

sites along Blister Creek had a distinct 'fingerprint' with respect to its absorbance and fluorescence properties, selecting for higher molecular weight humic-like materials of more extensive conjugation and aromaticity. This signature was not detected within Blister Creek itself. Although fluorescence excitation emission matrix spectra (EEMS) did not detect appreciable humic-like fluorescent material in Blister Creek, a residual protein-like fluorescence peak was identified. LC-OCD results indicated higher proportions of biopolymers and low molecular weight neutrals at the top of Blister Creek. LC-OCD results also clearly delineated overland seepage sites of from Blister Creek itself, with much higher proportions and concentrations of humic substances (Aukes, Dainard, Schiff).

We examined how water quality changed as it flowed from a soil/permafrost thaw seep through the Skeleton Lake subcatchment before entering Lake Hazen. Average concentrations of NO_2+NO_3 were 22.3 ug/L in water coming out of the seep, but were below levels of detection at all sites downstream. Average concentrations of TP in water coming out of the seep were low (2.5 ug/L) compared to those in the glacial rivers, and remained low throughout the remainder of the subcatchment (3.7-5.6 ug/L). Both unfiltered and filtered MeHg concentrations were low in water initially seeping from soils/permafrost (0.018 ng/L). Unfiltered MeHg concentrations increased as water moved through Skeleton Lake (0.075 ng/L) and two downstream ponds (0.370 ng/L). MeHg concentrations declined as water flowed downstream through the *Carex* grass dominated wetlands and the tundra creek channel prior to entering Lake Hazen at a concentration of ~0.026 ng/L (St.Louis, St.Pierre).

Samples for ^{3}H and $\delta^{18}O$-H_2O in glacial inputs and Lake Hazen indicate that the water residence time has decreased in recent years consistent with the increased glacial melt input (Aukes, Dainard, Schiff).

The Skeleton Lake water column temperature records showed that this small lake was thermally stratified between 6-17 July. Over this period, dissolved O_2 concentrations and % saturation increased in the bottom of Skeleton Lake. Concentrations of chlorophyll were also greatest at the bottom of the lake, between 3.5-4.3 m depth. Skeleton Lake water column profiles (Figure 3) found highest quantities of blue-green algae [relative fluorescence units (RFU)] at the lake bottom. These data all suggest that primary productivity is highest at the bottom of this relatively shallow lake where autotrophs (i.e. phytoplankton, blue-green algae) occur. It is also worth noting that there are large mats of submerged mosses on the bottom of Skeleton Lake that significantly contribute to primary productivity there (Lehnherr, Wisniewski, Varty).

4) The metabolism of Lake Hazen itself:

Water column chemistry (including contaminants) (St.Louis, Talbot, St.Pierre, Aukes, Dainard, Cavaco, Serbu): As in 2015, water column chemistry in Lake Hazen during the open water season in early August 2016 was very different from the water column chemistry previously measured under the ice. For example, following winter, we typically find that below 180 m, O_2 concentrations start declining and CO_2 concentrations begin increasing, due to active microbial metabolism in the sediments of Lake Hazen and no physical mixing of the watercolumn under the ice. However, in summer, both O_2 and CO_2 concentrations were, for the most part, similar throughout the entire 265 m of the water column. Evidence of distinct turbidity currents at the bottom of Lake Hazen in mid-summer show direct influence of glacial rivers on Lake Hazen bottom waters. Concentrations of NO_2+NO_3 were on average 28 ug/L throughout the Lake Hazen watercolumn, with little variation. Average concentrations of TP and SO_4^{2-} in the watercolumn were 2.5 ug/L and 11 mg/L, respectively.

For contaminants, we previously found that snowmelt increased MeHg concentrations from ~0.020 ng/L to ~0.075 ng/L in surface waters during the important spring bloom of biological activity under the lake ice. MeHg concentrations were extremely low (<0.007 ng/L) throughout the watercolumn after the height of

Figure 3. Igor Lehnherr and M.Sc. student Victoria Wisniewski sampling the watercolumn of Skeleton Lake (Credit: P. Aukes).

summer glacial melt and soil/permafrost thaw inputs, all of which were higher in MeHg concentrations.

Sediment microbial processes and diversity (St. Pierre, Poulain, Ruuskanen, Colby): Oxygen was depleted within the first centimeter of all cores, even in the summer months when the full water column was oxygenated, suggesting very active microbial respiration in the sediments. H_2S concentrations in the sediments were below detection. NO_2^- and NO_3^- concentrations increased in waters overlying cores collected from the deep site and decreased throughout the core, while NH_3 concentrations increased below the sediment-water interface, suggesting active nitrogen cycling.

Despite the low quantity of DNA in sediments (high inorganic material content), all of the marker genes tested so far (16S rRNA, *glnA* and *merA*) have been amplified with PCR without problems. The mercury reductase gene *merA* seems to be amplifiable down to at least 27 cm from the sediment surface. 16S rRNA gene amplicons have been sequenced from the following cores: Lake Hazen 2014 (deep and shallow cores: 0-1 cm), and 2015 (deep, shallow and John's Island cores: 0-5cm), Pond 1 and Skeleton Lake 2015 (spring and summer). Genes encoding enzymes involved in N, C and S cycles will also be targeted; primer design and selection is in progress.

Bioinformatic pipelines were developed during 2016 to analyze the 16S rRNA gene sequencing data. Lake Hazen had a slightly higher microbial diversity than Skeleton Lake, and both lakes, and the three sampling sites within Lake Hazen, all contained distinct communities. There did not seem to be a large difference between the communities sampled within the same site at Lake Hazen in 2014 and 2015. Gradients of H_2S, pH and redox potential in the sediments and water depth at the sampling sites were significantly correlated to the taxonomical and inferred functional composition of the sediment microbial communities at both lakes. The most common phyla at Lake Hazen and Skeleton Lake were Proteobacteria, Bacteroidetes, Chloroflexi, Actinobacteria and Acidobacteria. Organisms affiliated with chemoheterotrophy dominated the communities in both lakes. Lake Hazen had higher levels of taxa affiliated with nitrification processes: ammonia oxidation, nitrification and nitrite oxidation than Skeleton Lake, suggesting the presence of an active nitrogen cycle. Microbes in Skeleton Lake were more often affiliated with photoautotrophy and sulfate respiration than in the Lake Hazen samples. Taxa affiliated with intracellular parasitism of eukaryotes were also among the most common functional groups.

DISCUSSION

1) Net exchange of energy, water, CO_2 and CH_4 between the atmosphere and terrestrial landscapes in the Lake Hazen watershed (now revised to focus on the net exchange of CO_2 and CH_4 between the atmosphere and aquatic ecosystems in the Lake Hazen watershed):

Our previous study showed that the net ecosystem exchange (NEE) of CO_2 on the semi-desert landscape in the Lake Hazen watershed was most influenced by moisture, with wetter surface soils resulting in greater soil respiration and CO_2 emissions. At a wetland site, soil heating enhanced plant growth, which in turn increased CO_2 uptake. When using ecosystem-cover classification mapping, and data from this previous study, we found that freshwaters were unimportant contributors to total watershed carbon exchange, in part because they covered less than 10% of total area in the watershed. High Arctic watersheds are experiencing warmer and wetter climates than in the past, which may have implications for moisture availability, landscape cover, and the exchange of CO_2 and CH_4 of underproductive but expansive polar semi-desert ecosystems.

CO_2 concentrations in the glacial rivers declined with increasing flow intensity during the summer, an observation consistent with active geochemical weathering. Indeed, the fact that the declines in dissolved CO_2 occur concomitantly with increases in the dissolved concentrations of key weathering indicators (e.g., SiO_2, SO_4^{2-}, DIC) lends further support to this idea. Glacial environments have an abundance of recently comminuted and therefore geochemically active sediments because of the sheer mass of glaciers moving over the landscape during glacial advance and retreat. As atmospheric CO_2 dissolves into the glacial meltwaters laden with finely ground particulate, CO_2 is consumed during carbonate/silicate dissolution reactions (sample reactions shown below). Moreover, as these rivers enter Lake Hazen, Lake Hazen too becomes a CO_2 sink. During the summer melt season, our results suggest that the rivers and Lake Hazen, which together dominate the watershed, are a sink for atmospheric CO_2 at least over a short time each summer.

$$Ca_{1-x}Mg_xCO_{3\,(s)} + CO_{2\,(aq)} + H_2O_{(l)} \leftrightarrow (1-x)Ca^{2+}_{(aq)} + xMg^{2+}_{(aq)} + 2HCO^-_{3\,(aq)}$$

$$CaAl_2Si_2O_{8\,(s)} + 2CO_{2\,(aq)} + 2H_2O_{(l)} \leftrightarrow Ca^{2+}_{(aq)} + 2HCO^-_{3\,(aq)} + H_2Al_2Si_2O_{8\,(s)}$$

2) Net mass change of glaciers in the Lake Hazen watershed:

Climate change is greatly enhancing glacial melt in the Lake Hazen watershed, especially since ~2007. This is resulting in up to 10 times more water and sediment loads entering Lake Hazen each year during the summer melt period than prior to 2007 (Sharp, Danielson, Mortimer). Further, increased glacial runoff has changed the water residence time of Lake Hazen. Thus there is a lag between Lake Hazen water chemistry and chemical inputs to the lake from glacial rivers, for example. Lake Hazen is not at steady state with respect to its inputs, and as a result, we can use this lag to understand the importance of in-lake processes.

3) Chemical inputs to Lake Hazen from snowmelt, glacier melt and soil/permafrost thaw:

Average concentrations of TP were higher in glacial rivers than in the moat of Lake Hazen, or at the

Ruggles River outflow, suggesting that a large portion of the TP entering the lake settles out on particles. Concentrations of MeHg in the Ruggles River were lower than any of the inflow concentrations, suggesting that a combination of sedimentation, dilution and photodemethylation is occurring in the lake.

Concentrations of TP, PC, PN, MeHg in the Snowgoose River and Blister Creek increased with increasing river flow, possibly due to greater erosion intensity. Filtered MeHg concentrations were consistently lower than unfiltered concentrations throughout the summer in both the Snowgoose River and Blister Creek, further suggesting that a large portion of the MeHg in the rivers was particle bound and erosional in origin.

The NO_2+NO_3 coming out of the uppermost soil/permafrost thaw seep was quickly used up downstream, suggesting that these types of subcatchments in the Lake Hazen watershed are very N-limited, and rely on efficient recycling of organic-N (e.g., DON). Average concentrations of TP in water coming out of the seep were very low compared to those in the glacial rivers, and remained low throughout the remainder of the subcatchment before entering Lake Hazen. As such, these types of subcatchments are not important sources of P to Lake Hazen. MeHg concentrations increased as water moved through Skeleton Lake and two downstream ponds, indicating that these were both sites of active microbial Hg methylation, which will be resolved using the Hg stable isotope incubation experiment results. Unlike glacial rivers, a much larger portion of the MeHg was in the dissolved phase and not particle bound, making the MeHg much more readily bioavailable for bioaccumulation in these systems. MeHg concentrations declined as water flowed further downstream, though, suggesting that MeHg was either sequestered or demethylated in these latter sites of the landscape catchment.

Lake Hazen contained low DOC concentrations (<1 mg/L), which may be representative of its primary water source: glacial rivers (DOC <1 mg/L). However, the terrestrial subcatchment contained the highest DOC concentrations (Figure 4). Small permafrost streams appeared to result in localized productive zones, contributing higher concentrations of DOC (2 to 4 mg/L) to surrounding creeks and rivers. Surprisingly, DOC from the subcatchment contained very little ultra-violet or visible light absorbing components. The increased proportion of biopolymers in DOC from Skeleton Lake suggest a contribution of authochthonous C to the DOC pool, which indicates increased microbial contribution along the Skeleton Lake subcatchment.

Together, DOC concentrations, absorbance, and fluorescence measurements suggested that although Blister Creek seepage sites were more OC-rich, these small inflowing volumes were diluted extensively by glacial melt water in Blister Creek itself. This allowed the clear delineation of ‘terrigenous’ seepage site and ‘glacial’ Blister Creek DOM. Based on results of DOC concentrations, absorbance, and fluorescence analyses, Blister Creek DOM was expected to be low molecular weight, recalcitrant material, potentially sourced from autochthonous production by glacier ice algae. This working hypothesis appears to be supported by higher fluorescence intensities of protein-like fluorescent material sampled at the top of Blister Creek compared to samples taken further down-gradient. LC-OCD results indicated higher proportions of biopolymers and low molecular weight neutrals at the top of Blister Creek, which could support this hypothesis. LC-OCD results also clearly delineated overland seepage sites from Blister Creek itself, with much higher proportions and concentrations of humic substances being found in the seepage sites.

Preliminary results comparing Blister Creek to other glacial rivers and Lake Hazen appear to show similar DOC concentrations as well as absorbance and fluorescence spectra in most cases, although only a fraction of samples collected from 2016 have been analyzed and processed, so we look forward to addressing this further with greater resolution for the dataset in the near future. The same can be

Figure 4. Igor Lehnherr holding a peat core from the wetland in the Skeleton Lake subcatchment that was used for mercury methylation incubation experiments (Credit: V. Wisniewski).

said for LC-OCD, stable carbon isotope (δ^{13}C-DOC, δ^{13}C-DIC), and radiocarbon analyses (Δ^{14}C-DOC, Δ^{14}C-DIC).

4) The metabolism of Lake Hazen itself:

Water column chemistry: We believe that O_2 concentrations start declining and CO_2 concentrations begin increasing below 180 m in Lake Hazen under the ice due to active microbial metabolism in the sediments of Lake Hazen (see below), and no physical mixing of the water column under the ice. However, in late July 2015 and again in early August 2016, both O_2 and CO_2 concentrations were uniform throughout the entire 265 m of the water column due to physical mixing initiated by dense glacially-derived turbidity currents transporting surface river waters rapidly to the bottom of the lake.

Our few samples of δ^{15}N-POM for Lake Hazen suggest that the Lake may be N limited. Indeed, there are very few N sources in this N impoverished landscape.

Concentrations of MeHg throughout the water column in late July, early August were lower than concentrations measured in May under the ice, and much lower than in river water flowing into Lake Hazen. These results suggest that this contaminant is being stripped from the water column on particles that are rapidly settling out to the bottom of the lake, or is rapidly photoreduced in the surface waters of Lake Hazen.

Sediment microbial processes and diversity: Even in cores collected following ice-out, with an overlying oxygenated watercolumn, O_2 was depleted within the first centimeter of all cores regardless of the depth from which sediments were collected in Lake Hazen, suggesting very active microbial respiration in sediments (Figure 5). This also suggests that there are significant amounts of OC fueling this microbial respiration, the source of which we will continue to pursue in 2017. Preliminary data from δ^{13}C-DIC coupled with δ^{13}C-POM suggests that the source of the sediment CO_2 flux is the decomposition of POM produced within the lake at the sediment-water interface. The 16S rDNA studies support the conclusions drawn from chemical data and show a strong presence of chemoheterotrophic bacteria in the top sediment layer of Lake Hazen. The presence of a variety of obligate intracellular bacteria in the sediments (e.g., Legionella, Rickettsia, Aquicella) suggests an active eukaryotic community in the sediment, probably grazing on the microbes and contributing to recycling of carbon and nutrients within. In addition, taxa affiliated with the complete nitrification cycle are present, explaining the increased levels of NO_3^- in the bottom waters. Skeleton Lake sediments were dominated by phototrophic organisms that probably contributed to the high autochtonous DOC in the water column. The structuring of sediment (and soil) microbial communities by chemical gradients such as pH and redox potential is a well-known phenomenon since they impose constraints on their basic energy metabolism, enabling their growth and survival only in their optimal range. H_2S is produced by sulfate respiring bacteria (dependent on redox potential) but simultaneously inhibits the growth of microbes sensitive to it, which leads to a change in community structure. In addition it seems that water depth, as a proxy of, for example, light availability and particle settling dynamics that affect nutrient input into the sediment, seems to correlate significantly in the structuring of the sediment microbial communities. The sediment microbial communities at Lake Hazen seem to be highly heterogeneous, shaped by availability of light and nutrients, and further the establishment of differing chemical and redox potential gradients through microbial activity. Ongoing statistical analyses of the data will reveal which taxa and inferred functional groups are significantly affiliated with these environmental gradients, and the magnitude of changes in their abundance. The detection of *glnA* and *merA* at depth suggests the presence of a bacterial community that is resistant to mercury. We suggest that the mercury resistance gene is ancient and we are working at testing this hypothesis using bioinformatic methods developed in our lab.

CONCLUSION

Although it is "early days", it is tempting to speculate about changes in Lake Hazen and its watershed. There are a large number of system positive and negative feedbacks to consider. Increased glacial melt will

Figure 5. Vincent St.Louis, Charley Talbot (ECCC) and M.Sc. student Maria Cavaco sectioning a sediment core from 263 meters depth in Lake Hazen for biogeochemical and microbial parameters (Credit: J. Serbu).

deliver more water and sediment to Lake Hazen, decreasing the water residence time and diluting nutrients. Lake productivity may not respond to a longer ice-free season with lower nutrient inputs. Increasing runoff from the productive areas of the Lake Hazen terrestrial catchment will unlikely compensate for this increased glacial input. For the terrestrial catchment, the balance between increased precipitation may be more than compensated by increased evaporation (due to increased temperature). However, permafrost thaw may lead to increases in water availability in downslope areas, leading to increased terrestrial productivity. The water balance and thus the trajectory of arctic ponds (more or less ponds) cannot yet be predicted. Export to the nearshore marine environment will be affected by changes in the terrestrial catchment (including in lakes) but the lag will depend on water balance and storage times in the terrestrial catchment.

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IMPACTS OF THE CHANGING GLOBAL ENVIRONMENT AT NUNAVUT'S NORTHERN FRONTIER

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Microbial oxygen dynamics in permafrost thaw lakes
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Paleolimnological approach for examining carbon pathways in high latitude lake food webs
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Diversity and dynamics of aquatic viruses from the Canadian High Arctic in a climate change context
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Mass balance and the spatial variability of accumulation on White Glacier, Axel Heiberg Island, Nunavut
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Influence of thawing permafrost on aquatic food webs
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ABSTRACT

Global climate models predict that the greatest warming effects of greenhouse gas accumulation in the atmosphere will be at the highest latitudes of the Arctic, and consistent with these projections the High Arctic appears to be warming at rates well above the global mean. Over the first three cycles of ArcticNet, we have established observatories at Ward Hunt Island and along the adjacent northern coastline of Ellesmere Island: Nunavut's northern frontier. These sites have proven to be strategic research locations for detection and analysis of environmental change given the diversity of ecosystems in this region, their extreme sensitivity to perturbations of the cryosphere (snow and ice-containing environments), and the current trend of accelerated warming at these far northern latitudes (82-83N). For Phase 4 of ArcticNet, we have assembled a team of eight research laboratories with complementary expertise to evaluate climate change and its effects, with emphasis on the cryosphere (snow, ice and permafrost) and aquatic environments (lakes and fiords) of this coastal Arctic region. Our specific objectives include application of ArcticNet monitoring protocols for climate, snow and permafrost ground temperatures; development of a new indicator of climate change (snow thermal conductivity); analysis of changes in the Milne Ice Shelf and its associated ecosystems; mapping of the surface motion of northern glaciers and estimates of their mass balance (including the longest record for Canada); analysis of the timing, size and duration of shore and flaw leads; tracking of the ice islands that have originated from northern Ellesmere Island and NW Greenland, and modelling of their drift and decay as marine hazards; analysis of lake and fiord sediments to determine long term climate variability; biodiversity analysis of the network of microscopic life (including viruses) that supports northern aquatic ecosystems; and new measurements of aquatic food web structure, including by way of novel imaging techniques. Our overarching aim is to produce a subregional IRIS of northern Ellesmere Island that will be nested within a broader regional impact study (IRIS-2 of ArcticNet), and that will contribute to international, circumpolar initiatives that are currently underway or proposed.

KEY MESSAGES

- Our research continues to underscore how the northern coastline of Ellesmere Island, at Nunavut's northern frontier, contains diverse ice features and associated ecosystems.
- These ecosystems are vulnerable to global change. Our results from Milne Fiord, for example, show that there was a large shift in the microbial food web over the period 2011-2012, that the damming ice is continuing to thin, and that its epishelf ecosystem, the only one left in the Northern Hemisphere, is now on the brink of extinction.
- We have performed the first extensive measurements of snow physical properties in a polar desert. Our data may shed some light on the impact of desert characteristics on snow properties, which in turn affect the ground thermal regime.
- Our work has revealed a rich microbial community and associated food web in Nunavut's most northerly lake (and thus the most northerly in Canada): Ward Hunt Lake. Our molecular analyses revealed a surprisingly diverse benthic biofilm assemblage that may be sensitive to ongoing changes in lake ice, mixing and oxygenation.
- Viruses are an abundant, dynamic and important component of the microbial community of aquatic environments yet they remain relatively understudied in the lakes and coastal marine waters of the Canadian High Arctic.
- Land-terminating glaciers in the Canadian High Arctic have undergone a marked slowdown over the past 50+ years, with the terminus of White Glacier, Axel Heiberg Island, slowing by approximately half over this period.
- Breakup of floating glacier termini is ongoing within Yelverton Fiord and Inlet; Walker Glacier, one the northernmost glaciers of North America, retreated by another 10 m over the period 2013-2016.

- We developed a relatively inexpensive technique to conduct high-precision survey ice island and iceberg sails and are using parts of this workflow to develop an analogous technique for iceberg keels.
- We have an 11-month long dataset which revealed 5 m of thinning from our ice island thickness measurement system in Baffin Bay.
- We developed a new low-cost iceberg drift tracker, which was deployed on seven icebergs in northern Baffin Bay and Nares Strait in August 2016.
- Icebergs in Baffin Bay drifted at average speeds of up to 14.6 km/day, over total distances of up to 1650 km, in late summer and fall 2016.

OBJECTIVES

We continued to pursue the objectives identified in 2015, at the start of our ArcticNet Phase IV project:

1. Apply ArcticNet monitoring protocols for climate, snow and permafrost ground temperatures at stations along the Nunavut northern coastline to determine the year-to-year variability and long-term changes.
2. Develop and apply a new indicator of climate change: snow conductivity. This key variable is determined by snow metamorphism, and has critical feedback effects on permafrost stability.
3. Track and digitize all ice islands that have originated from northern Ellesmere Island and NW Greenland since 2008; deploy tracking beacons and model the drift and decay of ice islands (marine hazards).
4. Continue observations on glaciers and ice caps in northern Nunavut and their temporal variations, including the White Glacier, Axel Heiberg Island.
5. Undertake sediment core sampling to improve the understanding of the variability in northern Ellesmere Island climate over the last 5000 years by way of paleolimnological analysis.
6. Measure the water column properties, including plankton, of lakes and fiords along the northern Ellesmere Island coastline and their physical dynamics.
7. Analyze the microbial networks that underpin northern lake and fiord ecosystems, with attention to the molecular biodiversity of viruses and protists.
8. Synthesize pertinent information concerning northern Ellesmere Island in a way that can be used in ArcticNet, AMAP and other climate impact assessments.

KNOWLEDGE MOBILIZATION

- Production of curated data sets, and publication of these data in Nordicana D as open access available to all users including northern communities.
- Public lectures in Canada, often with senior Canadian policy makers present (e.g. ArcticNet; CMN Biodiversity Symposium, Ottawa), and similar outreach lectures locally (e.g., CEGEP St Lawrence) and abroad (e.g. Japan).
- Many presentations at scientific conferences, plus symposium organisation.
- Various interviews with online, print and broadcast media (e.g. video interviews at ArcticNet ASM).
- Translated our Nunavut Research Institute Reports into Inuktitut and circulated to Grise Fiord, Resolute and Iqaluit.
- Translated our Parks Canada Report into Inuktitut; this was then tabled at the Joint Parks Management Committee meeting in Iqaluit, with community representatives from Grise Fiord, Resolute and Iqaluit.

- Presented and discussed our work at the international forums, including by our students at the International Symposium in Microbial Ecology (ISME), and at the upcoming meeting of the International Arctic Science Committee in Prague (Vincent is the Canadian delegate for the terrestrial working group and former international vice chair of the TWG).
- Participated in ArcticNet Annual Science Meeting at many levels, from oral presentations and posters to organisation of a symposium (by Copland on glaciers), to chairing the final plenary discussion on the future of Arctic science.

INTRODUCTION

This project continues our work on along the northern coastline of Ellesmere Island, Nunavut's (and Canada's) northern frontier. Global climate models predict that the greatest warming effects of greenhouse gas accumulation in the atmosphere will be at the highest latitudes of the Arctic, and consistent with these projections, the High Arctic appears to be warming at rates well above the global mean. Over the last 10 years, we have established a set of observatories along the High Arctic coastline at the northern limit of Nunavut, in Quttinirpaaq National Park and adjacent areas: Nunavut's northern frontier (Figure 1). These sites have proven to be strategic research locations for detection and analysis of environmental change, given the diversity of terrestrial, freshwater and marine ecosystems in this region, their extreme sensitivity to perturbations of the cryosphere (snow and ice-containing environments), and the current trend of accelerated warming at these far northern latitudes (reviewed in Vincent et al. 2009 & 2011). The central objective of this project is to evaluate climate change and its effects on the Northern Ellesmere coastal environment, with emphasis on the cryosphere (snow, ice, permafrost) and aquatic environments (lakes, fiords), and to make comparative measurements on lake, snow and ice systems (including icebergs and glaciers) further to the south.

The cryosphere is responding to recent changes in climate. Snow is a critical and ubiquitous environmental compartment of high latitude regions and its physical properties strongly impact the energy budget of the surface and of the ground. Snow physical properties are largely determined by meteorological conditions, which govern snow metamorphism, i.e. recrystallization processes of snow crystals due to changing thermodynamic variables. With climate change, snow physical properties are expected to change and to feedback on climate. Ice shelves of northern Ellesmere Island have substantially changed over the last decade (Mueller et al., 2017). A lack of regeneration suggests that ice shelf loss is irreversible (Copland et al., 2007; White et al., 2015; Copland et al., 2017), after being in place for millennia (Antoniades et al., 2011; Antoniades 2017; England et al., 2008; 2017). Since 2002, ice shelf break-up has led to the loss of layers of freshwater that have been held in place between coastal ice and the shore (Mueller et al., 2003). The Milne Fiord epishelf lake is the last of its kind, and it is opportune to study the properties of an intact lake to draw conclusions regarding former epishelf lakes in the region (Hamilton et al., Submitted). Our research focuses on the past and current state of the ice shelves and the epishelf lakes and examines the link between their recent decline and climate as well as oceanographic warming/change. The trajectory and distribution of ice islands (large tabular icebergs) (see Van Wychen and Copland, 2017) is relevant to the operational mandate of the Canadian Ice Service (CIS), and this information is used in turn by Transport Canada and industry. Calving rates of glacier ice tongues and ice shelves are increasing dramatically (Peterson, 2005) at a time of increased Arctic marine traffic creating an additional need for ice hazard information. Operational models of iceberg drift and deterioration must therefore be extended to the ice island case with appropriate parameters such as geometric characteristics and model outputs must be validated against observations. In order to improve models and to better understand the ice island deterioration process, we have been instrumenting ice islands to follow their drift and melt. Research is also being conducted to examine ice island deterioration

Figure 1. Snow measurements with field instruments in May 2016, at the Ward Hunt Island climate station (Quttinirpaaq National Park., Nunavut). This is the northernmost, land-based environmental monitoring station in the world, and has been operated continuously as a result of ArcticNet funding from 2004 to the present (Photo credit: Florent Domine, CEN/ArcticNet).

using remote sensing, improving the detection of ice islands using polarimetric synthetic aperture radar and examining the ecological implications of ice islands.

The lakes, inlets and fiords of northern Ellesmere Island have long been recognized as sentinels of climate in the past and present (Bradley et al. 1996; Mueller et al. 2009; Vincent et al. 2011). Planktonic and benthic microbial communities often dominate these high latitude ecosystems but they are still not very well characterized. In particular, wild viruses play a critical yet understudied role in the Arctic microbial communities. Our research addresses the biodiversity, structure and dynamics of these high latitude microbial food networks.

ACTIVITIES

We completed another extremely successful season of field work along the northern coast of Ellesmere Island, and all objectives were completed as planned. In fact we had one of our longest field seasons to date, with subprojects running from May to July 2016.

A field camp was established at Purple Valley (rear of the Milne Ice Shelf) for approximately a week in July 2016 to service existing weather stations and time-lapse cameras on the Milne Ice Shelf.

We undertook a snow project at Ward Hunt Island in May-July 2016, and downloaded our Ward Hunt Island climate stations plus our satellite station at Lake A. We have downloaded data from our thermal conductivity data logger, which functioned successfully throughout the year. We have also studied in detail 10 snow pits over various environments: gravel, fine grained mineral soil with no vegetation, moss and lichen with thin organic soil over fine grained mineral soil or gravel (Figure 2).

We continued our long term measurements of permafrost monitoring and automated cameras on Ward Hunt Island in July 2016, including the new installation on our 10 m tower overlooking the snow monitoring site and downloaded instruments on deployed in 2015 to monitor the thermal conductivity of snow. Snow thermal conductivity was measured with heated needle probes and three needle probes were positioned on a post at heights of 2, 8 and 14 cm. As planned, we obtained the first year of data during May 2016.

We recovered instruments that have been recording temperature in Lake A, and continued our water column profiling in this lake. Time-lapse cameras were downloaded and serviced to provide monitoring of Disraeli Fiord, the Milne Glacier and floating ice tongue, and to monitor ice shelf breakups in our absence.

We recovered an acoustic Doppler current profiler and salinity and temperature loggers that were installed in the outflow channel near the seaward edge of the Milne Ice Shelf in July 2015.

Ice-penetrating radar was used to survey of the outflow channel at the seaward edge of the Milne Ice Shelf. We were able to access the water-column in the channel at two places and conduct several CTD casts and profile current velocity to repeat observations from 2015. We conducted CTD, current and turbidity profiles at the grounding line of the Milne Glacier to track subglacial inflow of meltwater. We serviced a small ablation stake network on the Milne Glacier and floating ice tongue and downloaded temperature loggers at each stake (Figure 3).

We surveyed the grounding zone and mid-line of the Milne Glacier with ice-penetrating radar completing some 40 km of transects. We tested an Uninhabited Aerial Vehicle (UAV) which did not function very well due to the proximity of the magnetic North Pole. We used a helicopter to take aerial photographs of the grounding zone of the Milne Glacier. We deployed three satellite tracking beacons on ice islands near Milne Ice Shelf and in Yelverton Bay. These data are being collected by the International Arctic Buoy Program (IABP) and are publicly available.

Figure 2. Snow field work at Ward Hunt Island in 2016. Left: ArcticNet student Maria Belke-Brea examining snow crystals after making spectral albedo measurements. Right: Snow pit showing an unexpected structure of wind slabs without basal depth hoar.

Figure 3. ArcticNet student Jill Rajewicz and Adjunct Professor Greg Crocker install a temperature sensor on an ablation stake on the Milne Glacier (Photo credit: Mike Taekema, ArcticNet).

An aerial photographic survey of the glaciers at the rear of Yelverton Inlet was undertaken in July 2016 to derive digital elevation models of their surface using the Structure from Motion technique. These will be compared with historical digital elevation models to compute changes in glacier thickness and volume over time.

Fieldwork was undertaken on White Glacier for two weeks in May 2016 to continue the long-term mass balance record there and to service existing weather and GPS stations.

A new high resolution SLR time-lapse camera was installed overlooking the terminus of Trinity Glacier, SE Ellesmere Island, to monitor iceberg production patterns at its terminus. Two differential GPS systems were installed across the ablation area of Trinity Glacier to monitor both short- and long-term variations in ice motion. This glacier has almost tripled in speed since 2000, so these measurements help to understand why and how the glacier will evolve in the future.

In August we used the helicopter on the *Amundsen* to deploy a total of 13 tracking beacons on icebergs and ice islands in northern Baffin Bay and Nares Strait: six on behalf of Environment and Climate Change Canada, and seven as part of our project to understand the patterns and controls on iceberg drift in this region. We used the *Amundsen* helicopter to make the first thickness measurements of ~8 tidewater glaciers along the east coast of Ellesmere Island with the use of a ground penetrating radar system. This provides information needed for the calculation of iceberg fluxes to the ocean from this region.

We undertook physico-chemical profiling of the water column of Milne Fiord (Neige Bay) in July 2016. Water samples were collected at different depths for nutrient, pigment, microscopic and molecular analyses in order to assess viral and microbial diversity. DNA analysis is now in progress. Additional samples were taken for planktonic food web analysis (Figure 4).

Milestones for 2016-17

- Publish the multidisciplinary synthesis of knowledge about northern Ellesmere Island Ice Shelves, in a book edited by Copland & Mueller (31 March 2016): This huge synthesis has taken a long time and massive effort to bring to completion, and it is a core component of our mini-IRIS. The final manuscript for this book was submitted to Springer at the end of December 2016, and is currently being typeset. An ISBN and marketing materials for the book are currently being organized, with publication of the final printed version anticipated by spring 2017.
- Compile and publish Milne Fiord ice shelf and under ice hydrographic data (31 March 2016): One manuscript is now submitted to JGR and is under revision (Hamilton et al. 2017a); another is under final revision for submission to The Cryosphere (Hamilton et al. 2017 a,b).
- Publish ice melt model and Petersen Bay hydrography papers (31 March 2016): This ice melt model was developed as an undergraduate thesis, which has now been completed and accepted: Garbo, A (2016) Glacier mass balance

Figure 4. ArcticNet student Myriam Labbé collecting zooplankton samples from Neige Bay, Milne Fjord in 2016 (Photo credit: Denis Sarrazin, CEN/ArcticNet).

modeling of the Milne Glacier, Ellesmere Island, Nunavut, BSc Honours thesis, Department of Geography and Environmental Studies, Carleton University, Ottawa. The results will require additional analysis for subsequent publication. Additional data was published in: White, A., Mueller, D. and Copland, L. (2015): Reconstructing hydrographic change in Petersen Bay, Ellesmere Island, Canada, inferred from SAR imagery. Remote Sensing of Environment, 165, 1-13. doi: 10.1016/j.rse/2015.o4.017.

- Publish new Digital Elevation Model and mass balance record of White Glacier (1 May 2016): This has now been published as: Thomson, L., Zemp, M., Copland, L., Cogley, G. and Ecclestone, M. 2016. Comparison of geodetic and glaciological mass budgets: White Glacier, Axel Heiberg Island, Canada. Journal of Glaciology, doi: 10.1017/jog.2016.112.
- Publish a synthesis paper on the limnology of Ward Hunt Lake (31 May 2016).
- We have published the data from Ward Hunt Lake in the online open access archives NEIGE (2017a) and NEIGE (2017b), and have compiled oxygen and other data in the article Mohit, Culley, Lovejoy, Bouchard & Vincent (2017) to be submitted shortly.
- Complete Year 2 field work with comparative work at Resolute Bay and Cambridge Bay; upload data to Nordicana D and PDC (1 Nov 2016).
- Work at Resolute Bay and Cambridge Bay was undertaken in 2014-15, and will be further extended once the CHARS base is operational.
- Northern Frontier team meeting and consultation with northern, national and international partners at ArcticNet Annual Scientific Meeting; IRIS-2 and sub-regional IRIS meetings (10 Dec 2016): Representatives of each component of Northern Frontier met at the ArcticNet ASM in Winnipeg, 6 December 2016, to discuss progress and ongoing plans.
- Publish Purple Valley climate data in Nordicana D (31 Dec 2016): This process has now been initiated with the technical editor of Nordicana D, for the publication: Copland, L. 2017. Climate station data from Purple Valley, northern Ellesmere Island, Nunavut (2009-2016), v 1.0. Nordicana D (in preparation).
- Curate all ice island data and publish in a publicly available geodatabase (31 Dec 2016): These data have now been curated and compiled and made publically available online via the publication: Mueller, D.R., Copland, L., Jeffries, M.O. 2017. Northern Ellesmere Island ice shelf and ice tongue extents, v. 1.0 (1906-2015). Nordicana D28, doi: 10.5885/45455XD-24C73A8A736446CC.

RESULTS

Climate monitoring

The 2016 summer season was warmer than the two previous years, and we suspect there will be ongoing large changes in the ice-dependent environments of the region. RADARSAT data indicate open water conditions in Disraeli Fjord (after we left) and large areas of open water in Ward Hunt Lake. We feel it necessary to install a camera system at ward Hunt Lake to capture these shifts with high resolution, and have planned to do this in July 2017. Weather conditions were extremely warm in Purple Valley in the summer of 2016, with a new record set for cumulative positive degree days (304 °C·d).These warm temperatures will likely increase the temperature and volume of the Milne Fiord epishelf lake, which will cause further melt of the underside of the Milne Ice Shelf (Hamilton et al., submitted).

Cryosphere measurements

The first continuous time series of snow thermal conductivity was obtained, showing unusual high values (Figure 5) and the absence of a soft basal depth hoar layer, which usually has a conductivity <0.1 W m^{-1} K^{-1} (Domine et al., 2016). Field measurements confirmed this and showed high density barely metamorphised wind slabs at the base (Figure 5). Preliminary interpretation invoke the persistent strong winds or the lack of soil moisture, which by releasing latent heat, keeps the ground warm and favor soft depth hoar formation.

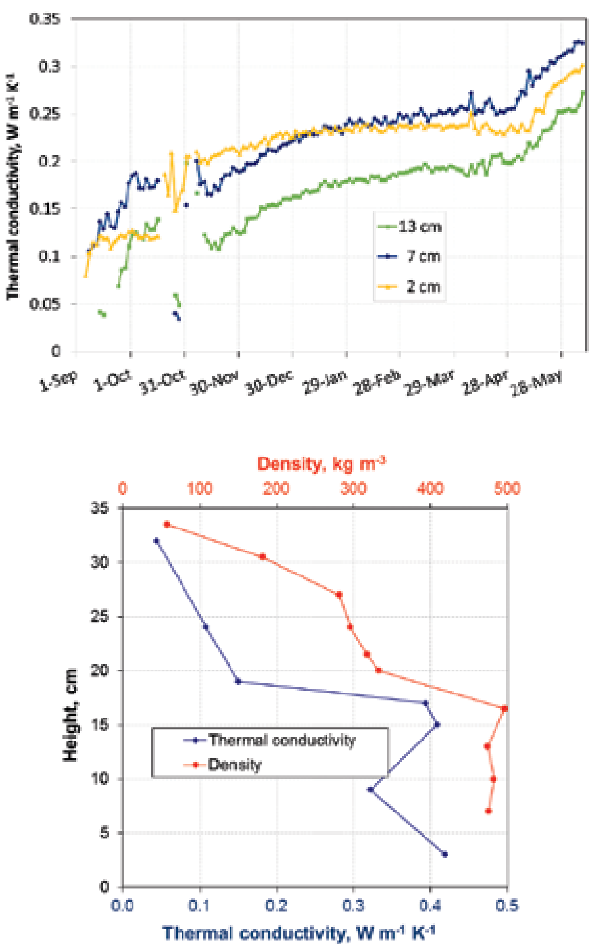

Figure 5. Measurement of snow physical properties at Ward Hunt Island. Top: continuous thermal conductivity measurements at three heights above ground, showing high values even at the very base of the snowpack. Bottom: vertical profile of snow density and thermal conductivity on thin rocky soil at a nearby spot (Source: Florent Domine, CEN/ ArcticNet).

It was unlikely that Ward Hunt Lake or the other lakes lost their ice cover in 2015, and despite multiple preceding years of cool conditions (in contrast to the period 2000-2012) there was no evidence of a return to thick ice covers, with around 2 m recorded in July 2016, and complete loss possible.

We documented the retreat of glacier termini in Yelverton Inlet and Fiord is ongoing, with breakup of most of the sea ice in this region by the end of summer 2016. Wed also remeasured the distance between reference poles installed in the 1950s and the terminus of the Walker Glacier (unofficial name), possibly Canada's northernmost glaciers (Figure 6). This showed that there has been a further retreat of 10 m over the last three years, from July 2013 (when we first discovered thus reference site established by Paul T. Walker on 10 July 1959) to July 2016.

Milne Fjord continued to show evidence of ongoing thinning of the ice shelf, however our results also draw attention to the importance of adjusting such records for the degree of ice meltwater generation each year. We discovered a 0.5 m s^{-1} jet of brackish water at about 8 m depth in the purported outflow channel in the Milne Ice Shelf. This, along with evidence from CTD profiles, is consistent with our hypothesis that the epishelf lake drains through at least one channel in the Milne Ice Shelf.

We have mapped several cross-sections of this channel from ice-penetrating radar data. This will be further analyzed to determine the cross-sectional area of the channel (to permit discharge calculations) and to examine the glacio-fluvial geomorphology of this inverted valley.

Our ablation stakes indicate the lower reaches of the Milne Glacier and Milne Glacier ice tongue have lost 1100 kg m^{-2} of ice, on average. A preliminary analysis of the horizontal movement of the Milne Ice Shelf using high-precision GPS data indicates that displacements of up to 20 m a year are typical.

Figure 6. The retreating terminus of Walker Glacier, one of the world's northernmost glaciers, in July 2016.

We overflew Thores Lake (Figure 7) inland from Disraeli Fiord. This is a proglacial lake and a class of ice-dependent ecosystem that is potentially sensitive to climate change. Our aim is to seek helicopter support next season to undertake the first measurements in this ecosystem type.

A new 1:10,000 map of White Glacier (Figure 8) was published, and received strong positive feedback. The map was awarded 1st place in ESRI Canada's GIS scholarship at the University of Ottawa and 2nd nationally. It has also been chosen for display at the Canadian map exhibit at the International Cartographic Association meeting in Washington, DC, in July 2017.

The long-term negative mass balance conditions at White Glacier continued in 2016. A paper was published in the Journal of Glaciology (Thomson et al., 2016) to describe the long-term mass balance of White Glacier over the period 1960-2014. The glacier thinned by an average of ~11.5 m over this time, with a comparison of mass balances derived from the geodetic method (i.e., digital elevation models) vs. the glaciological method (i.e., *in situ* measurement of stakes) showing no statistical difference. This indicates that field measurements provided an excellent record of mass balance conditions on an annual timescale.

Figure 7. Thores Lake in the Northern Frontier study region of Nunavut: an unexplored class of aquatic ecosystem subject to rapid change.

A comparison of modern (last four years) and historical (1960s) ice velocities on White Glacier show that it has slowed by almost half near the glacier terminus over this period. Velocity reductions have been less at higher elevations, but peaks in summer velocities are markedly higher today than in the 1960s. This suggests that basal sliding is becoming an increasingly important component of ice motion as surface melts are increasing. A paper was recently accepted for publication in the Journal of Glaciology that describes these results (Thomson and Copland, in press).

Based on helicopter overflights undertaken from the *Amundsen* in summer 2016, Humboldt Glacier was identified as a major source of ice islands for northern Baffin Bay. The northern part of the glacier front has accelerated and retreated over the past few years, releasing many hundreds of ice islands >1 km^2 in size.

Our climate station and automated ice-penetrating radar system in Baffin Bay eported with few interruptions from October 2015 to September 2016. The ice thickness was 110 m initially and lost 5 m over the measurement period. About 1.5 m of this was surface melt and the remainder was basal melt. Basal melt averaged 7 mm per day during the winter and this loss increased over the spring and summer months.

Limnological and paleolimnological measurements

Four sediment cores were obtained from Ward Hunt Lake at its deepest site and have been scanned

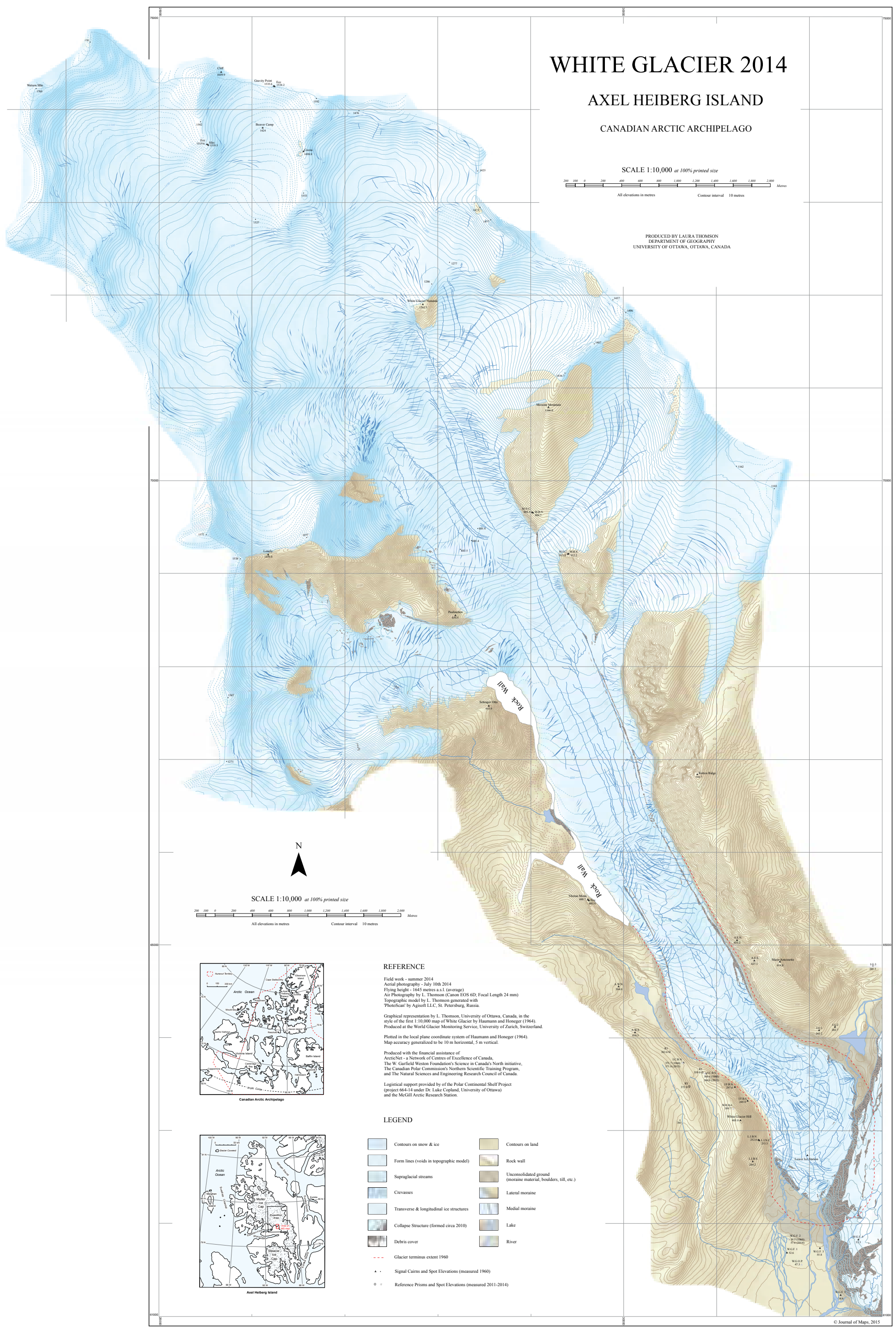

Figure 8. High-resolution map of White Glacier (Thomson and Copland 2016). © 2016 Laura Thomson.

(Figure 9). Stratigraphic analyses are currently underway. A student is doing his BSc thesis on this analysis.

Microbial network characterization

All sampling was completed for microbial DNA analysis. ArcticNet postdoc continued to develop and apply protocols for microbial network analysis; former ArcticNet postdoc Jérôme Comte (now research scientist at EC) continues to analyze the molecular data from Ward Hunt Island and this is moving into manuscript form. A synthesis of data for Ward Hunt Lake was presented as part of an international symposium on polar and alpine lakes as sentinels of environmental change that we organized in Turin, Italy in September 2016. Our analyses of molecular data including from the Northern Frontier sites revealed a new lineage of fungi that may be important in northern food webs (Figure 10).

Our analyses of the microbiology of Milne Fjord shows an unusually rich composition of biota that changes with depth, with dominance by green algae and many species of dinioflagellates (Figure 11).

We have optimized a relatively straight forward method to generate viral metagenomes that will greatly facilitate the production of these types of data from our remote sampling sites. In this method, sample is prefiltered to remove cells and then collected directly onto a 0.02 µm filter. The enriched viral communities on these filters are then extracted directly and sequenced.

We collected and are in the process of analyzing, metagenomic data generated from viral communities collected from different depths from Ward Hunt Lake, Lake A, Milne Fiord and Disraeli Fiord in the context of concurrent measurements of virus and bacteria abundance (Figure 12). Our preliminary analyses suggest that the phages from these sampling sites are highly dissimilar and vary according to depth.

The inoculation of cyanobacteria cultures with enriched virus communities from our three primary sampling

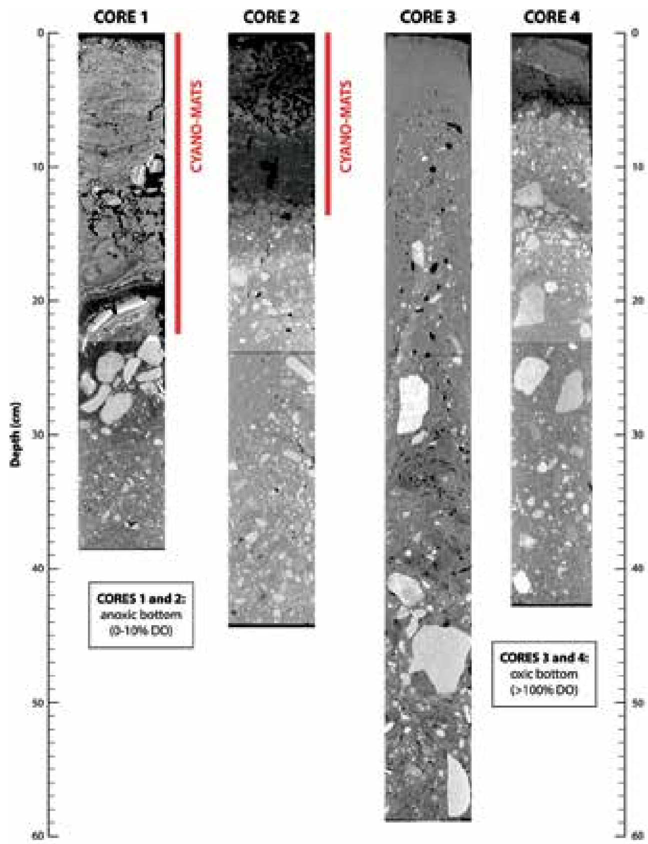

Figure 9. CT-scans of the four sediment cores from Ward Hunt Lake (Photo credit: Frédéric Bouchard, CEN/ArcticNet).

sites (Ward Hunt Lake, Lake A and Milne Fiord) has resulted in several candidate viruses. We are now in the process of isolating and amplifying these samples in preparation for sequencing.

ArcticNet data management

As throughout our past work in ArcticNet, we continue to help develop ideas and resources for the archiving, discovery and dissemination of northern data, and have submitted an article on this subject (Elger et al. 2017, Data Science Journal, in revision). We are continuing to develop Nordicana D as a bilingual, online, open-access doi-referenced data repository, and this now houses important ArcticNet data sets, cross-referenced in the Polar Data Catalogue. We were especially pleased that Nordicana D's application to be an

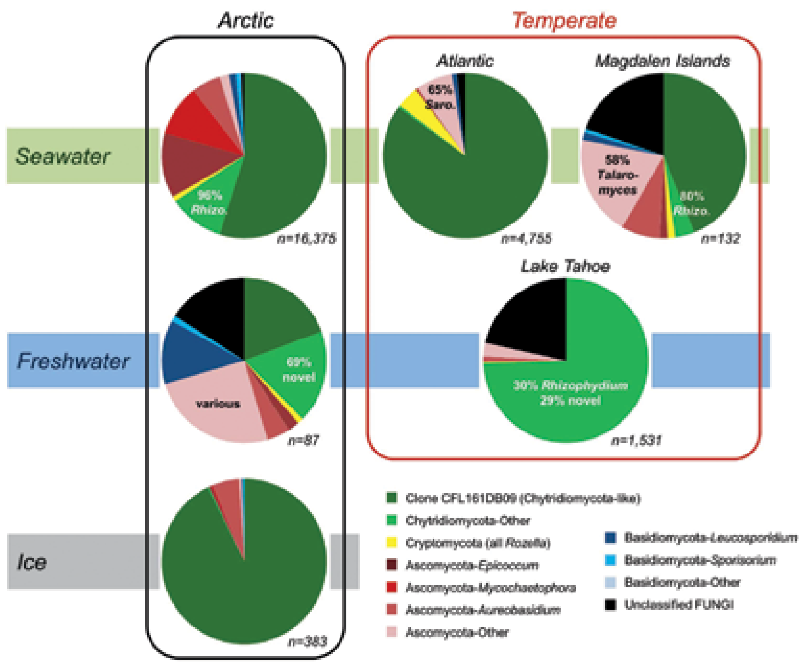

Figure 10. Molecular analyses of microbial samples compiled in Comeau et al. (2016), including data from the Northern Frontiers region. These show that freshwaters as well as sea water and ice contain diverse microfungi, including a new group of chytrids that may play an important role in aquatic food webs in Arctic waters as well as elsewhere.

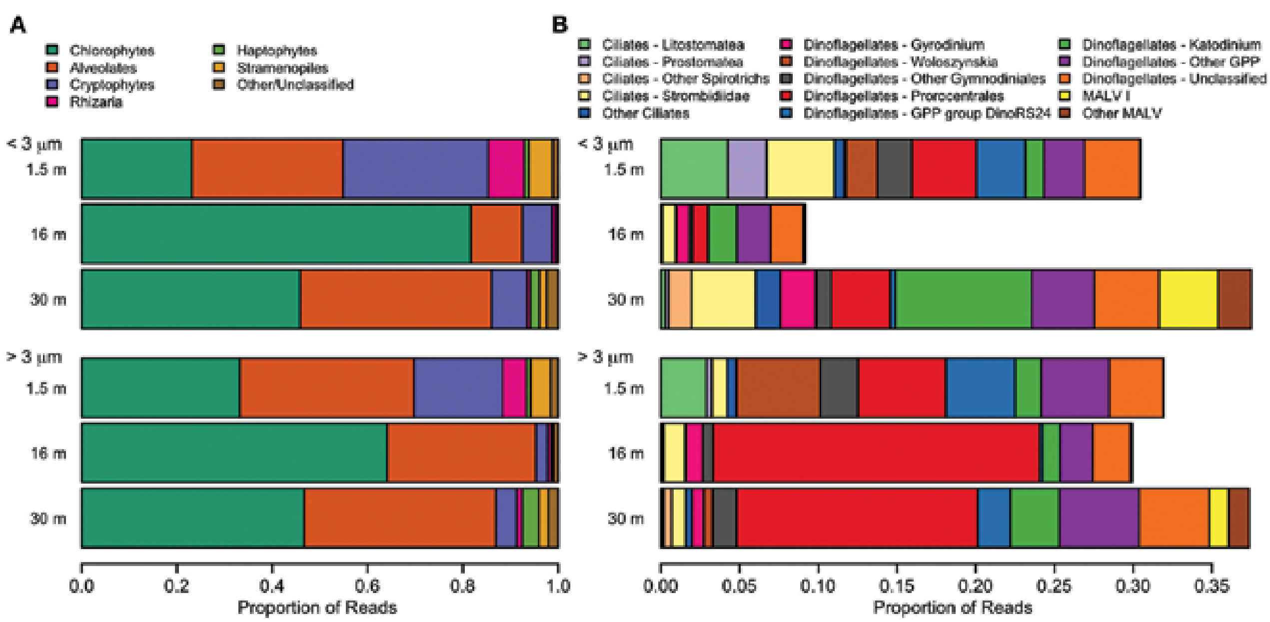

Figure 11. Microbial eukaryotes at three depths in Milne Fiord, showing the diversity of taxa and dominance by an unusual group of green microalgae. These results indicate the unique nature and biological richness of extreme ecosystems along the northern coast of Nunavut (published in Thaler et al. 2017). © 2017 Thaler, Vincent, Lionard, Hamilton and Lovejoy.

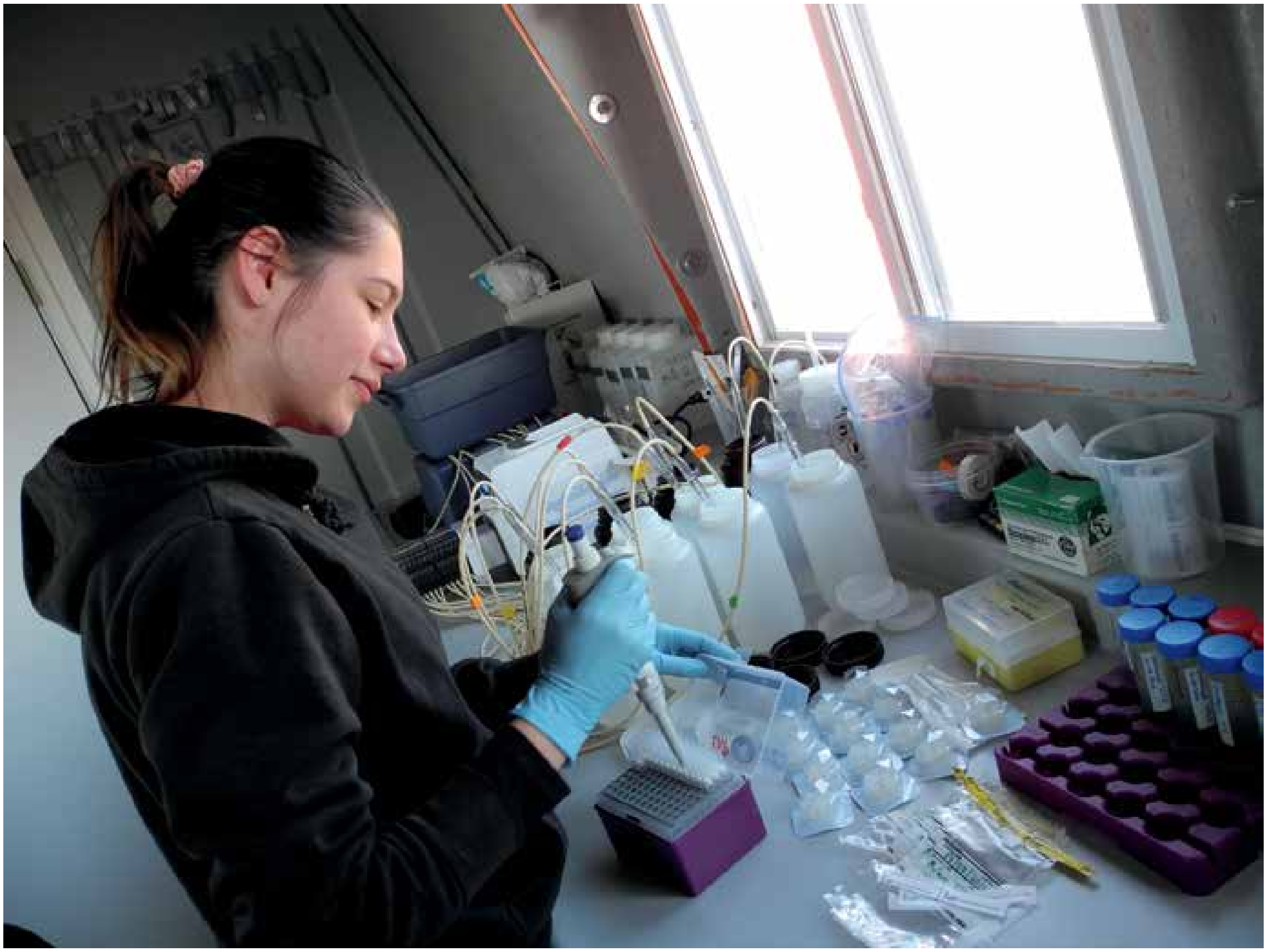

Figure 12. Preparation of samples in the field for viral analysis, by ArcticNet student Myriam Labbé at the laboratory on Ward Hunt Island, Nunavut, July 1016.

internationally recognized doi-based repository was accepted by the international consortium of publishers COPDESS, and that ArcticNet's Nordicana D data sets are now being cited in journals such as those published by the European Geophysical Union, the American Geophysical Union and John Wiley & Sons Inc (e.g. in Matveev et al 2016 Limnol Oceanogr). ArcticNet postdoc Mary Thaler helped publish an updated version of a reference DNA data base that can now be used to identify micro-organisms in Nunavut marine and freshwaters: Lovejoy et al. (2016).

DISCUSSION

Snow physical properties were untypical of the Arctic, as the usual soft highly insulating basal depth hoar layer was essentially absent in most places. We are investigating whether this was due to unusual meteorological conditions or to the characteristics of polar deserts, where low soil moisture would lead to rapid ground cooling, thus lowering the temperature gradient in the snowpack and slowing down metamorphism and depth hoar formation. This is a critical question. If soil moisture is the key, then warming will lead to enhanced depth hoar formation in the high Arctic, limiting ground winter cooling and therefore destabilizing permafrost. This would represent a strong positive feedback between climate, snow and permafrost.

Snow thermal conductivity data, together with meteorological data already being monitored on site, will be used to simulate snow properties, heat exchanges between the atmosphere and the snow and the ground thermal regime. Long term monitoring will allow the detection of changes in snow properties and simulations will help determine how these changes feedback on climate. Negative mass balance conditions for glaciers and ice shelves continued across the study area in 2016. Also, ice shelf breakups are continuing; for example, the Petersen Ice Shelf has continued its recent disintegration (White et al. 2015), together with rear of the Milne Ice Shelf. Large numbers of icebergs are currently present in northern Baffin Bay, together with many ice islands of several km^2 in size. Many of these have been produced from the recent acceleration and retreat of glaciers on Ellesmere Island and NW Greenland, and their drift tracks indicate that they can move >10 m per day when not grounded These may present a risk to shipping and offshore oil exploration in areas such as the Grand Banks in future years. Work is continuing on the use of >7000 Radarsat ScanSAR wide scenes obtained from the Canadian Ice Service to detect and characterize iceberg production patterns across SE Ellesmere Island, with initial results indicating a strong connection to sea ice breakout events. We have advanced our knowledge of the key features and processes that act to preserve or degrade the ice shelf, epishelf lake, floating glacier tongue and glacier in Milne Fiord. We have developed techniques to measure ice island and iceberg deterioration in the vertical (thinning) and horizontal (calving) dimensions. More than 30 freshwaters along have been sampled for water chemistry, plankton, food webs and watershed-lake coupling indicators. This dataset will be combined and analyzed collectively to provide a comprehensive understanding of how changing ice and snow conditions affect the biodiversity and productivity of high-latitude planktonic communities.

CONCLUSION

Our research on the snow, glaciers, icebergs, lake ice, ice shelves, permafrost, lake waters and northern fiords continues to yield new insights into the environmental features and ecosystem structure and dynamics of Nunavut. This work is revealing new levels of biodiversity that previously had not been imagined, for example the complex microbial biofilms that coat the bottom of Ward Hunt Lake, and the diverse ‘wild viruses’, that occur in all of the waters. This work is also deepening our understanding of the Nunavut cryosphere and its potential responses to global climate change, which is proceeding rapidly at these high northern latitudes, and in some cases creating new ice-hazards for maritime industries. Not only are these changes at Canada’s Northern Frontier important to track and understand for the people of Nunavut, but they are also of vital concern to all human society as sentinels of how fast our planet Earth environment is changing.

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SECTION III. INUIT HEALTH, EDUCATION AND ADAPTATION

Section III is composed of nine ArcticNet research projects covering many components of human health, housing and education under adaptation perspectives of climate change and modernization.

DESIGNING AND IMPLEMENTING THE NUNAVIK HEALTH SURVEY QANUIPPITAA 2016

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ABSTRACT

Approximately 1000 Inuit living in the 14 communities of Nunavik participated to the health survey entitled "Qanuippitaa? How are we?" during the fall of 2004. Twelve years later, there is a strong need to go back to the communities to document emerging issues arising in this small population in rapid transition, which is adopting a more sedentary lifestyle and new eating habits, while being confronted to a modified environment due to climate change. Following consultation with representatives of Inuit organizations and local health authorities over the last two years, it was decided that the Nunavik Health Survey Qanuippitaa 2016 will include three components: 1) a follow-up of the health status of the 2004 participants covering chronic diseases, infectious diseases and mental health; 2) a new youth cohort to identify indicators of health and well-being pertaining to this critical and underrepresented component of the Inuit population; and 3) a diagnosis of health and well-being at the community level. As in 2004, nutrition will be a central theme of the survey. A participative approach involving scientists, local health authorities and Inuit representatives will be used to define the outcomes of interest during the first year of the research program and launch our community of practice. New methodological tools and youth/community indicators will be developed and validated prior to the survey, which will take place during the fall of 2016. This multi-scale, interdisciplinary and participatory study will be critical for the development of multi-sectorial health, social and environmental policies, in order to promote Inuit health and well-being across all generations, and to foster Inuit culture and resilience for the many years to come.

KEY MESSAGES

- The Nunavik population is undergoing a rapid transition and there is a strong need to document emerging issues.
- The upcoming development of the Plan Nord will have major repercussions on the region. It is of utmost importance to accurately document the population's overall state of health for subsequent comparison purposes.
- The survey - now entitled Qanuilirpitaa? - is intended to provide stakeholders and authorities with solid ground on which to update policies and health programs in Nunavik, in particular to obtain the data required to support the next Strategic Regional Plan for health and social services.
- Themes to be addressed in the this participatory research have been defined together with Inuit co-researchers, representatives of the Nunavik Regional Board of Health and Social Services (NRBHSS) and in consultation with intersectoral organizations in Nunavik.
- The content of each theme was elaborated with experts from academia and refined through discussions with our Inuit co-leaders, NRBHSS representatives, clinicians in regional hospitals and members of key intersectoral organizations in Nunavik.
- The survey questionnaires were pretested in November 2106 with a small group of residents from Inukjuak. Final modifications are being effected for subsequent submission to CHU de Québec Ethics Board.
- The survey protocol was elaborated and will be submitted to CHU de Québec Ethics Board early in February 2017.
- Additional funding for Qanuilirpitaa? is being requested from the Northern Contaminants Program (Indigenous and Northern Affairs Canada) and the Canadian Institutes of Health Research.

OBJECTIVES

The health survey Qanuilirpitaa? 2017 includes three components, each with its specific sets of objectives:

1. Adult component

To assess adult health status in 2017 and follow-up on the adult participants enrolled in 2004 (N=700) in order to assess and compare trends, and recruit 300 additional participants aged 31 and older to ensure the representativeness of the adult cohort.

2. Youth component

Nesting this new youth cohort in Qanuilirpitaa? 2017 will allow us: 1) To complement the adult follow-up by recruiting a new group of 1000 Nunavimmiut aged 16-30 year-old; 2) To study the evolution of the prevalence of risk factors and diseases in the 18-30 year-old population between 2004 and 2017; 3) To document new emerging threats to health and new indicators of health and well-being pertaining to the younger generation.

3. Community component

To identify, define and assess culturally appropriate community indicators of health and well-being. Specific objectives are: 1) To define community health and well-being from the perspective of Nunavimmiut; 2) To identify and describe elements that foster community health and well-being; 3) To develop indicators to assess, and ways to describe, community health and well-being.

KNOWLEDGE MOBILIZATION

- Four presentations at scientific conferences
- Two interviews with online, print and broadcast media
- Participation in the Annual General Meeting of the Nunavik Hunters, Fishermen and Trappers Association in Salluit, November 14, to discuss the Qanuilirpitaa? Survey (Men's Health Theme)
- The Kativik School Board allocated funds for training young Inuit in health and environmental sciences in the framework of Qanuilirpitaa?
- Visited four Northern Communities for developing community health indicators (preliminary meetings in June 2016: Puvirnituq and Kangiqsujuaq; meetings to develop indicators: November 2016: Puvirnituq and Kangiqsualujjuaq)

INTRODUCTION

The health survey among the Inuit of Nunavik, entitled Qanuippitaa? – How are we? - was conducted in all 14 Nunavik communities from August 27th to October 1st, 2004. The general aim of the survey was to gather social and health information on a set of themes including various health indicators, physical measurements, and social, environmental and living conditions, thus permitting a thorough update of the health and well-being profile of the Inuit population of Nunavik. The survey was also intended to provide stakeholders and authorities with solid ground on which to update policies and health programs in Nunavik. Twelve years later, there is a strong need to go back to the communities to document emerging issues arising in this small population in rapid transition, which is adopting a more sedentary lifestyle and new eating habits, while being confronted to a modified environment due to climate change.

A workshop entitled "Inuit Health in Transition Study: The Circumpolar Cohort Nunavik Planning Meeting", convened by Nasivvik and other partners, took place June 11-13, 2012 in Kuujjuaq, Nunavik, to discuss the structure and priorities of future health studies in the region. Consultation meetings were also conducted with the Board of Directors and the Direction of

Public Health of the NRBHSS. During this two-year consultation process, it was decided that the next Nunavik Health Survey will include three components/goals: 1) To follow-up the 2004 Nunavik adult cohort; 2) To conduct the first Nunavik Inuit Youth and Young Adult Health Survey; 3) To identify, define and assess culturally appropriate community indicators of health and well-being. Each component has specific scientific, technical and ethical issues to be addressed during the first 17-months of the grant period. Scientific groups were constituted to define those issues for each component (see "Activities" below). The first two components comprise multiple markers of physical health (and diseases) as well as mental health and well-being, and will cover determinants of optimal health such as environmental contaminants, nutrition, substance use, sexual life, socioeconomic, psychosocial, family and community factors. The third component on community health and well-being is being developed with the aim of obtaining complementary quantitative and qualitative data at the community level in addition to the individual level. A transversal theme on nutrition was added because it is one of the most important determinants of health – not only with regard to its involvement in the etiology of chronic diseases – but also because it is a major target for public health interventions and/or community based-projects, which were mentioned during the 2012 workshop to be efficient in bringing positive changes in the communities.

ACTIVITIES

The governance structure of Qanuilirpitaa? 2017 involves the participation of many members of the Nunavik communities, reflecting the participatory approach that characterizes this health survey. This structure is overseen by a Steering Committee composed of key regional leaders and representatives from Nunavik as well as the three main partners (NRBHSS/INSPQ/CHU de Québec Research Centre/Laval University). In order to ensure the overall guidance of the health survey, two meetings of the Steering Committee were held in in June and October 2016; a third one is scheduled in March 2017. The Scientific Committee reports to the Steering Committee on the scientific orientations of the survey. Meetings of the Scientific Committee took place periodically during the 2nd year to oversee and support the development of the survey content, design and methodology. In addition to those committees, other committees were also active with several meetings during Y2: the Management Committee, the Logistic Committee and the Communication Committee.

Adult and Youth components

- Throughout the year, both the Adult component committee and the Youth component committee held several meetings to finalize tools, questions, clinical tests and analyses that will be used to assess the different themes and to monitor the components' progress.
- The leaders of each component met with academic experts to complete the development of the tools (questionnaires, clinical tests) for each theme.
- Discussions were held with NRBHSS staff, physicians practicing in Nunavik and clinicians to develop the follow up procedure for participants who will have abnormal test results.
- While the first year had been devoted to numerous consultations in Nunavik with regional and Inuit experts, intensive work took place during the second year to finalize the protocol for the adult and youth components. The different themes selected for the adult and youth components are presented below (see Activities).

Community component

- 1.5-day workshops were conducted in two communities in Nunavik (Sept. 2016):

   - In Inuktitut and/or English; audio recorded
   - Workshop facilitators: two academic researchers, two research assistants
   - Round table discussion and use of flip charts
- Workshop process
   - What does health and well-being? What does it mean to you?
   - What makes us healthy and well?
   - What in our community makes us healthy?
- Workshops were transcribed (as much as possible)
- Thematic analysis of the data was conducted using two documents as basis for analysis (NVivo):
   - Parnasimautik (report on community consultations to identify a comprehensive vision of development for the Nunavik region according to Inuit culture, identity, language and traditional way of life)
   - ITK Social Determinants of Inuit Health in Canada
- "Translation" of themes discussed by participants during the workshops into a list of potential indicators
- Questions were developed for inclusion in Qanuilirpitaa? questionnaires

RESULTS AND DISCUSSION

Adult and Youth components

Tables 1a and 1b presents the different themes that are included in the Adult and Youth components. These themes were presented during our Steering Committee meetings and approved. We are now preparing for the field work next fall and starting the communication campaign. Data generated from the Survey will be used to produce the survey highlights, thematic reports and scientific articles presenting relations between risk factors and health outcomes.

Community component

We have produced a detailed framework of community conditions and associated indicators that are important for the health and well-being of Nunavimmiut (with conceptual background and measurements methods).

During the next months, we will validate and refine themes and indicators with NRBHSS experts and community mayors. Data collection will take place during Qanuilirpitaa? next fall through questions included in the survey questionnaires and mapping of community resources and assets along identified themes. Each theme will be characterized (e.g. through interviews, focus groups, visual methods). Deliverables for each community will include a community assets mapping and a guidebook for action. With this information, communities can themselves follow and assess conditions and their change over time, set objectives for development, and assess progress or success toward community development objectives.

CONCLUSION

We have now completed the protocol for the Qanuilirpitaa? 2017 health survey, which will be submitted to the Steering Committee and CHU de Québec REB for approval. We are now getting ready for the field work onboard the CCGS *Amundsen* from mid-August to early October 2017.

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Table 1a. Table presenting the different themes that are included in the Adult and Youth components.

Themes included in *Qanuilirpitaa?* 2017	Targeted cohort
Sociodemographic information (including education, income, employment)	Youths and Adults
Subjective rating of overall mental and physical health (quality of life, self-rated health, satisfaction in life)	Youths and Adults
Mental health and well being (psychological distress, stress, suicide, traumas, historical loss, community attitudes toward mental health)	Youths and Adults
Resilience self-esteem	Youths and Adults
Social support	Youths and Adults
Victimization - Crime against property - Physical and sexual abuse - Childhood trauma - Elder's victimization - Bullying	 Youths and Adults Youths aged 17 and older and Adults Youths aged 17 and older and Adults Adults aged 55 and older Youths
Sexual health (sexual orientation, indicators of sexual health, perceived benefits of childbearing, risky sexual behaviors for STIs and pregnancies, pregnancy history)	Youths
Teenage pregnancy (socio-cultural factors influencing teenage pregnancy)	16-19 year old
Justice	Youths and Adults
Substance use and dependence, gambling	Youths and Adults
Media	Youths and Adults
Family (family relations and support, cohesion, family traumas (stressors, residential school, foster care))	Youths and Adults
Socio-cultural determinants of health (incl cultural identity, community involvement, equity and discrimination, social integration and exclusion, sprituality)	Youths and Adults
Housing and homelessness	Youths and Adults
Cardiometabolic health	Youths and Adults
Acute gastroenteritis infection and *Cryptosporidium* spp.	Youths and Adults
Zoonosis (rabies infection and risk of bites)	Youths and Adults
Zoonosis: *Toxoplasma gondii* and *Trichella* spp.	Youths and Adults
Helicobacter pylori	Youths and Adults
Oral Health	Youths and Adults
Respiratory health	Youths and Adults

Table 1b. Second section of Table 1a.

Themes included in *Qanuilirpitaa?* 2017	Targeted cohort
Men's health	Men from both cohorts
Women's health	Women from both cohorts
Nutrition/Food frequency questionnaire (FFQ)	Youths and Adults
Food security	Youths and Adults
Hunting and fishing	Youths and Adults

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COMMUNITY VULNERABILITY, RESILIENCE AND ADAPTATION TO CLIMATE CHANGE IN THE CANADIAN ARCTIC

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ABSTRACT

The Canadian Arctic is widely regarded as a global hotspot of climate change impacts. Implications will be particularly pronounced for Inuit, many of whom depend on hunting, fishing, and trapping; activities which continue to underpin livelihoods and economies, but which also create unique sensitivities to the rapidly changing climate. Communities will have to adapt to these changes and, in order to inform the development of adaptation strategies by households, communities, and governments, we need to know the nature and determinants of vulnerability and resilience to climate change. This research program seeks to expand our understanding of what makes communities vulnerable or resilient to the impacts of climate change. Focusing specifically on the Inuit harvesting sector, the program is underpinned by the development of a longitudinal community-based monitoring approach which will involve comparing the nature and determinants of vulnerability and resilience today with fieldwork conducted by team over a decade ago, and the creation of hunter monitoring teams to develop a real-time picture of how climatic conditions are experienced and responded to. With emphasis on real time monitoring, longitudinal analysis, and longterm collaboration, the findings of the work will help us examine and test conclusions reached by other studies, including our own, which we believe may not fully capture nature of vulnerability; unaddressed, we believe that policies based on existing knowledge could inadvertently be maladaptive. This novel approach will involve partnering with three Inuit communities from diverse areas of the Arctic (Ulukhaktok, NWT; Arctic Bay, NU; Rigolet, Nunatsiavut), and has an emphasis on creating science that can directly be used in decision making of our northern collaborators.

KEY MESSAGES

- This project is developing an understanding of the dynamics of community vulnerability and resilience in the subsistence harvesting sector.
- The project graduated four master's students in 2015-2016.
- Across case study communities, many climatic conditions that were problematic for hunting and travelling over a decade ago have persisted or worsened.
- Sensitivity to changing climatic conditions is largely conditioned by non-climatic factors and processes.
- Communities are adapting to changing conditions. However, the convergence of continuously changing climatic conditions with ongoing non-climatic processes have progressively restricted the ability of some to adapt, and several past adaptations that have proven maladaptive.
- Adaptation initiatives need to support flexibility along adaptive pathways rather than rigid adaptations.

OBJECTIVES

The overarching goal of this project is to develop a dynamic understanding of the processes and conditions affecting community vulnerability and resilience to the effects of climate change. The work is building on previous research by the team to develop and validate a longitudinal community-based monitoring approach. The project is working in the three communities specified in the original application: Ulukhaktok, NWT; Arctic Bay, NU; Rigolet, Nunatsiavut. Additonally, three communities have been incorporated into the project: NI Dr. Pearce is leading work in Paulatuk, NWT, to better understand the dynamics by which communities respond to novel change, specifically examining how the community adapted to the arrival of beluga in the region in the 1970s and 80s, a trend now happening in Ulukhaktok; PI Dr. Ford is leading work in Arviat, NU, where his team first conducted vulnerability and adaptation research in 2010 as part of a previous ArcticNet project; and PI Dr. Ford is working in Pangnirtung assessing community fisheries in-light of climate impacts. In addition to specific community-level work, the project is also linking into broader level adaptation planning in Canada, to international policy debates (UNFCCC), and global (e.g. IPCC 1.5C assessment), national (e.g. Natural Resources Canada Coastal Assessment), and regional assessments (e.g. AACA). Contributing funds from SSHRC, Rotary Foundation, and CIHR are supporting the work.

The overarching goal of the project will be achieved through five objectives:

Objective 1 – Conceptual development: Complete. This objective developed a conceptual approach for capturing the dynamic nature of vulnerability and resilience in Arctic communities.

Objective 2 – Methodological development: Complete. This objective developed and validated a novel, longitudinal community-based monitoring approach to identify and characterize the determinants of community vulnerability and resilience, and how they evolve over time.

Objective 3 – Empirical application: Ongoing. Data on vulnerability and resilience is being collected in partner communities, with the work focusing on two components of Inuit harvesting that have been identified as highly sensitive to climate change: wildlife management & utilization, and dangers of engaging in land based activities. Key activities include: i) a re-analysis on vulnerability and resilience in the three communities, comparing present day trends to previous work done by the team (Ford and Pearce), with work in Arctic Bay complete (Archer et al., 2016); ii) establishing community based monitoring teams in partner communities to document land use real-time using GPS units, and interview land users on a regular basis on the harvesting activities and coping mechanisms; iii) an examination of search and rescue data, and examining ways to enhance emergency response (Clark et al., 2016).

Objective 4 – Adaptation planning: Planned for year three (2017).

Objective 5 – Examine broader insights of the work: Ongoing. This objective involves ongoing reflection by the team and partners to evaluate the findings within the context of other research on the human dimensions of arctic change. Broader-level understanding of the dynamic nature of vulnerability and resilience will be derived from comparing the findings to past vulnerability research in these and other locations.

KNOWLEDGE MOBILIZATION

Conference presentations

- Clark, D. (2016) Health and Climate Change; beyond hurricanes and heatwaves. One Health Conference, November 2016, Iowa City, Iowa. [Invited Presentation].
- Clark, D. (2016) Evidence based practice and search and rescue. SARScene, October 2016, Edmonton, Alberta. [Invited Presentation].
- Clark, D. G., Ford, J., Berrang-Ford, L., Pearce, T., Gough, W., Kowal, S., (2016) Environmental Dimensions of Search and Rescue and Injury in Nunavut. Oral presentation. Transforming Health Care in Remote Communities, Edmonton, Alberta.
- Clark, D. G., Ford, J., Berrang-Ford, L., Pearce, T., Gough, W., Kowal, S., (2016) Vulnerability to injuries associated with land-use activities in Nunavut, Canada. Poster session. Transforming Health Care in Remote Communities, Edmonton, Alberta.
- Clark, D. Ford, J., Pearce, T., Berrang-Ford, L. (2016) Vulnerability to unintentional injuries associated with land-use activities and search and rescue in Nunavut, Canada. Poster session. ArcticNet Annual Scientific Meeting, December 5-9, Winnipeg, Manitoba.

- Clark, D. Ford, J., Pearce, T., Berrang-Ford, L. (2016) Vulnerability to unintentional injuries associated with land-use activities and search and rescue in Nunavut, Canada. Oral presentation. ArcticNet Annual Scientific Meeting, December 5-9, Winnipeg, Manitoba.
- Fawcett, D., T. Pearce, J.D. Ford, and L. Archer. (2016) Operationalizing longitudinal approaches to climate change vulnerability assessment. Oral presentation. ArcticNet Annual Scientific Meeting, December 5-9, Winnipeg, Manitoba.
- Fawcett, D., T. Pearce, J.D. Ford, and R. Notaina. (2016) A longitudinal approach to assessing vulnerability to climate change in Ulukhaktok, NT, Canada. Poster session. ArcticNet Annual Scientific Meeting, December 5-9, Winnipeg, Manitoba.
- Galappaththi, E. K., Clark, D., IK-adapt group. (2016) Early-career climate change adaptation Researchers' perceptions of and reflections in community-based research. Poster session. ArcticNet Annual Scientific Meeting, December 5-9, Winnipeg, Manitoba.
- Galappaththi, EK., Ford, JD. (2016) Opportunities for climate change adaptation: comparative research on Indigenous fisher communities in the Canadian Arctic and Eastern Sri Lanka. 5th Asia-Pacific climate change adaptation forum, October 17-19, Colombo, Sri Lanka.
- Jasiuk, L. and Pearce, T. (2016) Inuit women's conceptualizations of, and approaches to, health in the context of adaptation to a changing climate. Poster session. ArcticNet Annual Scientific Meeting, December 5-9, Winnipeg, Manitoba.
- Jasiuk, L. and Pearce, T. (2016) Inuit women's conceptualizations of, and approaches to, health in the context of adaptation to a changing climate. Oral presentation. ArcticNet Annual Scientific Meeting, December 5-9, Winnipeg, Manitoba.
- Labbé, J., Ford, JD., Flynn, M. (2016) Readiness for climate change adaptation in Nunavut, Canada. Poster session. ArcticNet Annual Scientific Meeting, December 5-9, Winnipeg, Manitoba.
- Labbé, J., Ford, JD., Flynn, M. (2016) Readiness for climate change adaptation in Nunavut, Canada. Oral presentation. ArcticNet Annual Scientific Meeting, December 5-9, Winnipeg, Manitoba.
- Labbé, J., Flynn, M., Ford, JD. (2016). Adaptation and the big picture in Nunavut: an evaluation of its key linkages and barriers. Poster session. Adaptation Futures, May 10-13, Rotterdam, Netherlands.
- Lede, E., Pearce, T., Ford, J. (2016) The Role of Multiple Stressors in Adaptation to Climate Change in Paulatuk, NT Poster session. ArcticNet Annual Scientific Meeting, December 5-9, Winnipeg, Manitoba.
- Parker, C. (2016). Examining the vulnerability of an Inuit food system to climate change in the context of climatic and non-climatic stressors: a case study of Ulukhaktok, NT. Thesis defense presentation. Department of Geography, University of Guelph, June 07, Guelph, Ontario.
- Pearce, T. (2016). Inuit TEK, subsistence hunting and adaptation to climate change in the Canadian Arctic. Oral presentation. ArcticNet Annual Scientific Meeting, December 5-9, Winnipeg, Manitoba.
- Pearce, T. (2016). TEK and adaptation to climate change in the Arctic. Invited presentation at the UNESCO Indigenous Knowledge and Climate Change Conference, Marrakech, Morocco, 2-4 Nov. 2016.
- Pearce, T. (2016). The adaptation challenge: lessons from the Canadian Arctic. Invited presentation at the UNESCO Pavilion, COP22, Marrakech, Morocco, 8 Nov. 2016.
- Sawatzky, A., Cunsolo, A., Bunce, A., Gillis, D., Shiwak, I., Shiwak, J., Wood, M., Ford, J., Furgal, C., Edge, V., the Rigolet Inuit Community Government., Harper, S.L. (2016) Participatory

development of environment-health surveillance in the Canadian Arctic. Oral presentation. Sparking Population Health Solutions Summit, April 2016, Ottawa, Ontario.

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- Sawatzky, A., Cunsolo, A., Gillis, D., Cook, O., Shiwak, I., Flowers, C., Wood, M., the Rigolet Inuit Community Government, Harper, S.L. (2016) Exploring Inuit perspectives on developing values-based environment and health metrics for surveillance in Rigolet, Nunatsiavut, Labrador. Oral presentation. OVC 2016 Graduate Student Research Symposium, November 2016, Guelph, Ontario.
- Sawatzky, A., Cunsolo, A., Gillis, D., Cook, O., Shiwak, I., Flowers, C., Wood, M., the Rigolet Inuit Community Government, Harper, S.L. (2016) Developing values-based environment and health metrics for surveillance with Inuit in Rigolet, Nunatsiavut, Labrador. Oral presentation. ArcticNet Annual Scientific Meeting, December 2016, Winnipeg, Manitoba.
- Sawatzky, A., Cunsolo Willox, A., Harper, S.L., Shiwak, I., Wood, M., IMHACC team, the Rigolet Inuit Community Government. (2016) Inuit-identified pathways for good wellbeing: An exploration of the land's role as a determinant and source of wellness in Nunatsiavut, Labrador. ArcticNet Annual Scientific Meeting, December 2016, Winnipeg, Manitoba.

Organized special sessions at conferences

- Ford, J. (2016). What we can learn for adaptation from the Arctic. Panel presentation in the Indigenous Peoples Pavilion, COP22, Marrakech.
- Ford, J. (2016). Understanding adaptation in the Arctic. Chair and presenter, Adaptation Futures, Rotterdam, May 2016.
- Ford, J. (2016). Adapting to climate change in the Canadian Arctic. Panelist and Chair, Adaptation Canada, 2016, April 14th, Ottawa.
- Cunsolo A., Harper S.L., Sawatzky, A., Gillis, D., Cook, O., Shiwak, I. (2016) Inuit-led participatory environment and health monitoring for adaptation and sovereignty. Panel presentation. Inuit Studies Conference, St. John's, Newfoundland and Labrador.

Workshops organized

- Community based monitoring and climate adaptation workshop, McGill University, June 9th - 10th 2016.
- Results sharing workshop, Iqaluit, April 26th 2016.

Media

- November 25th 2016. Op-ed by James Ford and Dylan Clark in the Montreal Gazette "An inclusive approach to Canada's climate change challenges" http://montrealgazette.com/opinion/columnists/opinion-an-inclusive-approach-to-canadas-climate-change-challenges.
- September 2016. Research profiled in National Geographic "Arctic-search-and-rescue-missions

double" http://www.nationalgeographic.com/adventure/features/arctic-search-and-rescue-missions-double.

- August 23, 2016. Research profiled on Arctic Deeply "Unraveling the Accidents of Climate Change" https://www.newsdeeply.com/arctic/articles/2016/08/23/unraveling-the-accidents-of-climate-change.
- July 25th, 2016. Research profiled on CBC News "New research confirms Arctic travel riskiest in spring and fall" http://www.cbc.ca/news/canada/north/nunavut-research-search-and-rescue-risks-1.3693006.
- April 12th, 2016. Research profiled on CBC News "Arviat program aims to lower rising search and rescue numbers" http://www.cbc.ca/news/canada/north/nunavut-land-program-search-and-rescue-1.3530966.

INTRODUCTION

The implications of climate change will be particularly pronounced for Canadian Inuit, many of whom depend on hunting, fishing, and trapping, activities which continue to underpin livelihoods and economies, but which also create sensitivity to the rapidly changing climate. Inuit will need to adapt, and this is reflected in the increasing urgency with which adaptation is being considered in the North. To initiate adaptation actions, decision makers and communities need to understand the nature of vulnerability to climate change in terms of who and what are vulnerable, to what stresses, in what way, and why, and capacities to adapt? This requires working with people in communities to identify what climatic stresses are relevant and important to communities beyond those selected *a priori* by researchers, including the role of non-climatic drivers of change. The last decade has witnessed a proliferation of vulnerability and resilience research in the Arctic to this end, which has provided important contributions for answering these questions. Team members have been in the vanguard of this research.

Despite advancements in our understanding of community vulnerability and resilience to climate change, the dynamic nature of vulnerability and its determinants remains incompletely understood, and we only have a general understanding of the factors creating vulnerability and underpinning resilience. For example, in the harvesting sector, we know that the climate is changing but the nature of the climate stimuli that present risks and/or opportunities have not been fully characterized; we know that adaptive learning has historically underpinned adaptation in the North, but few studies have examined how or how fast adaptive learning takes place; we know that hunters are adapting, but we have little understanding of how much disturbance can be adapted to or what climate stimuli promote adaptation; we know that there are likely time-lags and thresholds of adaptive response but our knowledge of them is limited; and we know that cumulative impacts of resource development and enhanced shipping access will affect how climate change plays out locally, but have little understanding of how.

Moreover, our knowledge of Inuit adaptation to climate change remains static. Vulnerability and resilience reside in the condition and operation of coupled human-environment systems, and are determined by: interactions between exposure, sensitivity, and adaptive capacity; the role played by restructuring after a stress(es) has been experienced; the influence of determinants operating over multiple scales; system feedbacks to stresses encountered; and internal dynamics that give rise to new risks and/or enhance resilience. These dynamic interactions are little understood in the Arctic or more generally, particularly with regards to risks surrounding Inuit harvesting (wildlife management & utilization, land dangers), and are constraining our ability to identify and examine potential future vulnerabilities and identify sustainable and effective adaptations.

This deficit in understanding stems from conceptual and methodological limitations of current work, which have typically utilized a retrospective study design where an understanding of the factors affecting vulnerability and resilience is derived from an assessment of how climatic conditions currently affect the subsistence sector and have done so in the past. This has generated a wealth of information on the determinants of vulnerability, but the retrospective nature of data collection presents challenges: interviewees often only recount what they have recently experienced, the season during which research takes place influences what is recounted, and details about the nature of risks and coping strategies recedes as time passes. This creates difficulties for understanding the role played by multiple stresses in affecting vulnerability and resilience, identifying the place-specific nature of risks, situating current experience in a broader historical context, and accounting for the evolution of vulnerability over time.

New approaches and methodologies are needed if we are to create a more dynamic understanding of vulnerability, the development and application of which underpin this ArcticNet project.

ACTIVITIES

In this section, we outline key activities undertaken in 2015- 2016.

Objectives 1 & 2: Conceptual development and methodological development

The conceptual and methodological development objectives were completed in 2015-16, building upon work done in the first year of the project. In one paper, led by master's student Fawcett and currently in review, we reviewed the literature on longitudinal monitoring approaches and proposed such an approach for climate change application in the Arctic. The paper, in turn, builds upon the completed master's thesis of Archer who reported on his use of a longitudinal based vulnerability assessment in Arctic Bay, NU. Another master's student, Clark, developed an approach for assessing vulnerability to injury among land-users in the Arctic. This framework and its application in various Nunavut communities is published in Social Science and Medicine (Clark et al., 2016). We also reviewed general community based vulnerability work in the Arctic to document trends in assessment and results, publishing the work in Environmental Research Letters (McDowell et al., 2016). In July, we organized a workshop at McGill on approaches to community based monitoring attended by NIs and project students, in addition to other scholars leading ArcticNet projects (e.g. Dr. Furgal and Dr. Harper). The workshop was well attended (n=25) with associated papers in preparation.

Peer Reviewed Articles

- Archer, L., Ford, J., Pearce, T., Gough, W., Kowal, S. (2017). Longitudinal assessment of climate vulnerability: A case study from the Canadian Arctic. Sustainability Science, 12(1), 15-29.
- Clark, D. Ford, J., Pearce, T., Berrang-Ford, L. (2016). Vulnerability to injuries associated with land-use activities in Nunavut, Canada. Social Science & Medicine, 169, 18-26.
- Ford, J., Stephenson, E., Cunsolo-Willox, A., Edge, V.L., Farahbakhsh, K., Furgal, C., Harper, S., Chatwood, S., Mauro, I., Pearce, T., Austin, S., Bunce, A., Bussalleu, A., Diaz, J., Finner, K., Gordon, A., Huet, C., Kitching, K., Lardeau, MP., McDowell, G., McDonald, H. Nakoneczny, L., and Sherman, M. (2016). Community-based adaptation research in the Canadian Arctic. WIREs Climate Change 7(2), 175-191.
- McDowell, G., Ford, J., Jones, J. (2016). Community level climate change vulnerability research: Trends, progress, and future directions. Environmental Research Letters 11 (3).
- Fawcett, D., Pearce, T., Ford, J. Archer, L. (in review). Operationalizing Longitudinal Approaches to Climate Change Vulnerability Assessment. Global Environmental Change.

Objective 3: Empirical application

In 2015-2016 we continued data collection in partner communities, obtained ethics approval for sub-projects that will be ongoing through 2017, and published work on land-user safety. Research activities during 2016 used both quantitative methods and qualitative methods to examine vulnerabilities at community and regional scales.

A study examining current states of vulnerability and adaptation in Arctic Bay was completed by master's student Lewis Archer who graduated in summer 2016. This work highlighted changes the community has undergone over the past fifteen years, such as changes in land use patterns, technology use as adaptation, and shifts in food security. A similar study is ongoing in Ulukhaktok, were data was collected from June to August 2016. This involved 32 semi-structured interviews, analysis of secondary sources, and participant observation. As with our Arctic Bay work, the study in Ulukhaktok aims to document how the community has experienced and responded to climatic and socio-economic change over the last 10 years since NI Pearce conducted the original vulnerability assessment. This involved working closely with two local Inuit researchers who were involved in collecting and analyzing interviews, provided cultural guidance to the researcher (including input into interview questions) and context for data, acquired some harvest and sport hunting data from the HTC and NWT ENR, and completed some mapping exercises for the project.

In Paulatuk, master's student Eric Lede is researching how social and physical systems influence adaptation. Lede conducted semi-structured interviews with 30 participants (15 males, 15 females) during the summer of 2016. Interviews were complimented with participant observation over nine weeks and analysis of secondary sources. Preliminary findings highlight the influence of stressors such as economic change and aspects of the education system on adaptive capacity. During fieldwork, master's student Lede was also a contributor to a workshop for the Paulatuk Climate Change Adaptation Plan and gave a community radio show on his work. This research study will continue into 2017 with anticipated publications in the third year.

This past year, master's student Dylan Clark finished his thesis which focused on search and rescue in and land safety among land-users in the communities of Arviat, Pangnirtung, and Whale Cove. This research has helped define the relationship between physical conditions and safety on the land, as well as outlining how individuals are adapting to changing risk and constraints to adaptation. Based on findings and community direction, Clark has been working with the community of Arviat to prevent search and rescues with Elder-youth mentorship on the land and exploring the use of drones for search and rescue response. In addition to Clark's work in Pangnirtung, Eranga, a PhD student, started preliminary fieldwork focusing on climate change adaptations in small-scale fisheries. In summer 2016 Eranga Galappaththi spends two weeks in Pangnirtung and a week in Iqaluit talking to fishers and potential research partners to get the feedback to PhD research on 'opportunities for adaptation.' The outcome of the visit is networking and positive comments from the community to incorporate into the research proposal.

In June 2016, master's student Colleen Parker successfully defended her thesis which examined the vulnerability of the food system in Ulukhaktok to climate change in the context of climatic and non-climatic stressors. The research sought to understand how climate change is impacting, and might further impact, key attributes of the community's dual food system including food availability, access, quality and storage. Consistent with the vulnerability approach to studying the likely impacts of climatic change, attention was directed to current climatic and non-climatic exposure-sensitivities and adaptations. Data were collected from secondary sources, semi-structured interviews with a cross-section of community members (n=39) and key informants (n= 3), and participant observation. The collected evidence reveals that multiple stressors, both climatic and non-climatic, impact food security. Further, the results point to the need for Inuit food sovereignty and reinforce both formal and informal adaptation mechanisms.

Dr. Ashlee Cunsolo, Dr. Sherilee Harper, and PhD student Alexandra Sawatzky have been working with communities in the Nunatsiavut region to understand how climate change monitoring can be done effectively and in-line with indigenous knowledge. Environment and health monitoring can be an effective strategy to estimate the magnitude, frequency, distribution, and determinants of diseases and conditions, detect outbreaks, understand the natural history of a disease, evaluate effectiveness of strategies, prioritise planning and resources, and respond with prevention and health promotion programing. Furthermore, these systems may also act as early warning systems to initiate advisories intended to protect public health, including boil water advisories or weather alerts. This project has also included three open houses, two design workshops in Rigolet, and development of an IPad app for data collection and monitoring. Rigolet resident, Charlie Flowers, is leading the research program from the community.

Publications

- Clark, D., Ford, J. Berrang-Ford, L., Pearce, T. (2016). The role of environmental factors in search and rescue incidents in Nunavut. Public Health, 137, 44-49.
- Clark, D., and Ford, J. (in press). Emergency response in a rapidly changing Arctic. CMAJ.
- Parker, C. (2016). Examining the vulnerability of an Inuit food system to climate change in the context of climatic and non-climatic stressors: a case study of Ulukhaktok, NT. MSc Thesis, Department of Geography, University of Guelph, Guelph, Ontario.
- Cunsolo, A., Harper, S., (2016) The Inuksuk Program: Community-Led Monitoring for Adapting to the Health Effects of Climate Change. Cape Breton University.
- Sawatzky, A., Cunsolo, A., Harper, S., (2016). The eNuk program: Developing a community-based, participatory health and environment surveillance strategy alongside Inuit in Rigolet, Nunatsiavut, Labrador. Memorial University; Labrador Institute.

Objective 4: Adaptation planning

Planned for year three (2017). The research findings will inform adaptation planning by generating information on the dynamic nature of vulnerability, and working closely with decision makers to this end. This activity will also be informed by an evaluation of the current state of the adaptation landscape in the north, which was undertaken with co-funding in 2015-16 with associated output listed below.

Publication

- Labbe, J., Ford, J., Araos, M., and Flynn, M. (in press). The government-led climate change adaptation landscape in Nunavut, Canada. Environmental Reviews.

Objective 5: Examine broader insights of the work

Ongoing. In 2015-16 this objective involved broad outreach activities associated with the UN climate change conference in Marrakesh where PI Ford convened a side event on adaptation in the Arctic, with panelists including the president of NTI and Chair of ICC-Canada. In addition, as part of broader engagement, Ford also had lead authorship roles in the Arctic Council's AACA assessment and Canada's national coastal assessment. PI Ford and NI Pearce also advised ITK in the creation of their Inuit priorities for Canada's Climate Change Strategy.

Publications

- Ford, J., Falk, K., Tesar, C. Adaptation and resilience. Chapter 11 in Adaptation Actions for a Changing Arctic Assessment, Arctic Council.
- Tesar, C., Falk, K., Ford, J. Summary of adaptations for the BBDS. Chapter 12 in

Adaptation Actions for a Changing Arctic Assessment, Arctic Council.

- Ford, J., Bell, T., and Couture, N.J. (2016): Perspectives on Canada's North Coast region; in Climate Change Impacts and Adaptation Assessment of Canada's Marine Coasts, (ed.) D.S. Lemmen, F.J. Warren, T.S. James and C.S.L. Mercer Clarke; Government of Canada, Ottawa, ON.
- Hoover C, Ostertag S, Hornby C, Parker C, Hansen-Craik K, Loseto L and Pearce T (2016). The continued importance of the hunter for Inuit food security. Solutions.
- Pearce, T. (2016) Inuit subsistence hunting and climate change: Ulukhaktok, NWT, Canada; in Adaptation Actions for a Changing Arctic (AACA) report for the Bering-Chukchi-Beaufort region.

RESULTS

Archer, L., Ford, J., Pearce, T., Gough, W., Kowal, S. (2017). Longitudinal assessment of climate vulnerability: A case study from the Canadian Arctic. Sustainability Science, 12(1), 15-29.

The Arctic is a global hotspot of climate change, which is impacting the livelihoods of remote Inuit communities. We conduct a longitudinal assessment of climate change vulnerability drawing upon fieldwork conducted in 2004 and 2015 in Ikpiarjuk (Arctic Bay), Nunavut, and focusing on risks associated with subsistence harvesting activities. Specifically, we employ the same conceptual and methodological approach to identify and characterize who is vulnerable, to what stresses, and why, assessing how this has changed over time, including re-interviewing individuals involved in the original study. We find similarities between the two periods, with many of the observed environmental changes documented in 2004 having accelerated over the last decade, exacerbating risks of land use: changing sea ice regimes and wind patterns are the most widely documented at both times, with new observations reporting more frequent sighting of polar bear and orca. Socio-economic and technological changes have altered the context in climate change impacts are being experienced and responded to, both exacerbating and moderating vulnerabilities compared to 2004. The adoption of new technology, including GPS and widespread use of the internet, has helped land users manage changing conditions while sharing networks remain strong, despite concern noted in the 2004 study that they were weakening. Challenges around access to financial resources and concern over the incomplete transmission of some environmental knowledge and land skills to younger generations continue to increase sensitivity and limit adaptive capacity to changing climatic conditions.

Clark, D. Ford, J., Pearce, T., Berrang-Ford, L. (2016). Vulnerability to injuries associated with land-use activities in Nunavut, Canada. Social Science & Medicine, 169, 18-26.

Injury is the leading cause of death for Canadians aged 1 to 44, occurring disproportionately across regions and communities. In the Inuit territory of Nunavut, for instance, unintentional injury rates are over three times the Canadian average. In this paper, we develop a framework for assessing vulnerability to injury (Figure 1) and use it to identify and characterize the determinants of injuries on the land in Nunavut. We specifically examine unintentional injuries on the land (outside of hamlets) because of the importance of land-based activities to Inuit culture, health, and well-being. Semi-structured interviews (n=45) were conducted in three communities that have varying rates of search and rescue (SAR), complemented by an analysis of SAR case data for the territory. We found that risk of land-based injuries is affected by socioeconomic status, Inuit traditional knowledge, community organizations, and territorial and national policies. Notably, by moving beyond common conceptualizations of unintentional injury, we can better assess root causes of unintentional injury and outline paths for prevention.

Clark, D., Ford, J. Berrang-Ford, L., Pearce, T. (2016). The role of environmental factors in search and rescue incidents in Nunavut. Public Health, 137, 44-49.

Objectives: Unintentional injury is a leading cause of morbidity and mortality in Nunavut, where the importance of land-based activities and reliance on semi-permanent trails create unique risk profiles (Figure 2 and Table 1). Climate change is believed to be exacerbating these risks, although no studies have quantitatively examined links between environmental conditions and injury and distress in the Canadian Arctic. We examine the correlation between environmental conditions and land-based search and rescue (SAR) incidents across Nunavut.

Study design: Case study.

Methods: Case data were acquired from the Canadian National Search and Rescue Secretariat (Figure 3 and Table 2). Gasoline sales from across the territory are then used to model land-use and exposure. We compare weather and ice conditions during 202 SAR incidents to conditions during 755 non-SAR days (controls) between 2013 and 2014.

Results: We show daily ambient temperature, ice concentration, ice thickness, and variation in types of ice to be correlated with SAR rates across the territory during the study period (Figure 4).

Conclusions: These conditions are projected to be affected by future climate change, which could increase demand for SAR and increase injury rates in the absence of targeted efforts aimed at prevention and treatment. This study provides health practitioners and public health communities with clearer understanding to prepare, respond to, and prevent injuries across the Arctic.

Clark, D., and Ford, J. (in press). Emergency response in a rapidly changing Arctic. CMAJ.

Wide disparities in both rates of unintentional injury and access to search and rescue services and emergency medical care exist between Southern and Northern Canada. Recent high-profile events in the Northwest Passage have drawn attention to the potential for a large-scale disaster in the Canadian arctic. With limited access to emergency medical care in Inuit communities, interventions to improve resilience — particularly in the face of the effects of climate change — and access to emergency medical response services are needed.

Fawcett, D., Pearce, T., Ford, J. Archer, L. (in review). Operationalizing Longitudinal Approaches to Climate Change Vulnerability Assessment. Global Environmental Change.

The past decade has seen a proliferation of community-scale climate change vulnerability assessments globally. Much of this work has employed frameworks informed by scholarship in the vulnerability field, which draws upon interviews with community members to identify and characterize climatic risks and adaptive responses. This scholarship has developed a baseline understanding of vulnerability in specific places and industries at particular times. However, given the dynamic nature of vulnerability new methodologies are needed to generate insights on how climate change is experienced and responded to over time. Longitudinal approaches have long been used in sociology and the health sciences to capture the dynamism of human processes, but their penetration into vulnerability research has been limited. In this article, we describe the application of two longitudinal approaches, cohort and trend studies, in climate change vulnerability assessment by analyzing three case studies from the Arctic where the authors applied these approaches. These case studies highlight how longitudinal approaches can be operationalized to capture the dynamism of vulnerability by identifying climate anomalies and trends, and how adaptations develop over time, including insights on themes such as social learning and adaptive pathways.

Ford, J., et al. (2016). Community-based adaptation research in the Canadian Arctic. WIREs Climate Change 7(2), 175-191.

Community-based adaptation (CBA) has emerged over the last decade as an approach to empowering

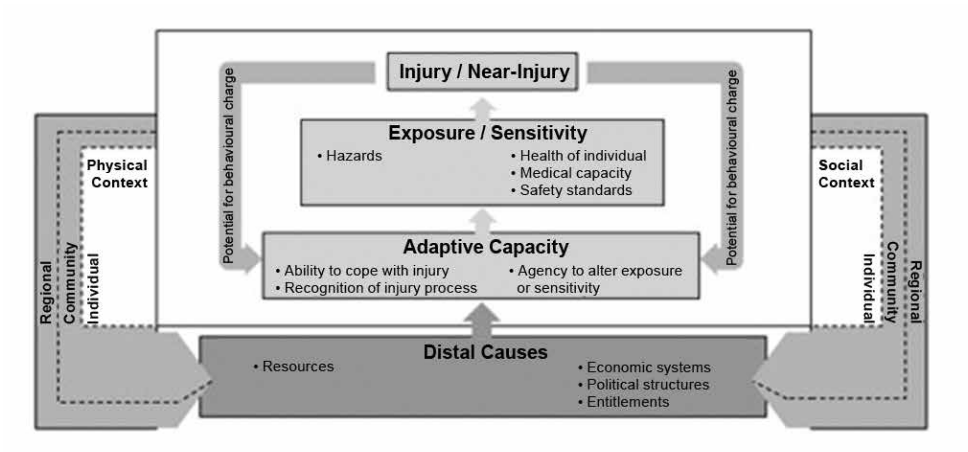

Figure 1. Shematics of the framework for assessing vulnerability to injury.

communities to plan for and cope with the impacts of climate change. While such approaches have been widely advocated, few have critically examined the tensions and challenges that CBA brings. Responding to this gap, this article critically examines the use of CBA approaches with Inuit communities in Canada. We suggest that CBA holds significant promise to make adaptation research more democratic and responsive to local needs, providing a basis for developing locally appropriate adaptations based on local/indigenous and Western knowledge. Yet, we argue that CBA is not a panacea, and its common portrayal as such obscures its limitations, nuances, and challenges. Indeed, if uncritically adopted, CBA can potentially lead to maladaptation, may be inappropriate in some instances, can legitimize outside intervention and control, and may further marginalize communities. We identify responsibilities for researchers engaging in CBA work to manage these challenges, emphasizing the centrality of how knowledge is generated, the need for project flexibility and openness to change, and the importance of ensuring partnerships between researchers and communities are transparent. Researchers also need to be realistic about what CBA can achieve, and should not assume that research has a positive role to play in community adaptation just because it utilizes participatory approaches.

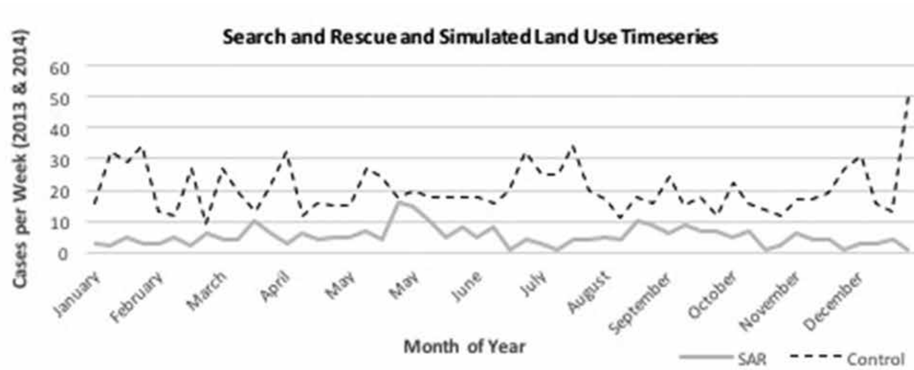

Figure 2. Search and rescue and simulated land use timeseries. Cases per week as function of month for period 2013-14.

Figure 3. Arctic search and rescues in 2014, map produced by authors with data from NSS.

Labbe, J., Ford, J., Araos, M., and Flynn, M. (in press). The government-led climate change adaptation landscape in Nunavut, Canada. Environmental Reviews.

The Canadian Arctic is uniquely sensitive to climate change impacts, including rapidly warming temperatures, sea ice change, and permafrost degradation. Adaptation—including efforts to manage climate change risks, reduce damages, and take advantage of new opportunities—has been identified as a priority for policy action across government levels. However, our understanding of adaptation in the Canadian North is limited: Is adaptation taking place, to what stresses, and what does it look like? In this paper, we answer these questions for the Inuit territory of Nunavut, systematically cataloguing and reviewing government-led adaptation programs and policies at community, territorial, and federal levels, drawing on publically available information. We documented a total of 700 discrete adaptation initiatives. The focus on adaptation to-date has primarily been at the groundwork level, aimed at informing and preparing for adaptation through impact assessments, adaptation planning exercises, and stakeholder engagement. Adaptation in Nunavut has been driven by cross-scale coordination and leadership from the territorial and federal government. Our study finds few examples of concrete actions for planned adaptation, such as changes to or creation of policies that enable adaptation, alterations to building codes and infrastructure design with changing geo-hazards, or enhanced disaster planning and emergency preparedness in light of projected impacts. This study indicates a need for formal adaptation plans for the Governments of Canada and Nunavut, emphasis on adaptation monitoring and evaluation, and a greater role of Inuit traditional knowledge and cultural values in adaptation policy.

McDowell, G., Ford, J., Jones, J. (2016). Community level climate change vulnerability research: Trends, progress, and future directions. Environmental Research Letters 11 (3).

This study systematically identifies, characterizes, and critically evaluates community-level climate change vulnerability assessments published over the last 25 years (n = 274). We find that while the field has advanced considerably in terms of conceptual framing and methodological approaches, key shortcomings remain in how vulnerability is being studied at the community-level. We argue that vulnerability research needs to more critically engage with the following: methods for evaluating future vulnerability, the relevance of vulnerability research for decision-making, interdependencies between social and ecological systems, attention to researcher / subject power dynamics, critical interpretation of key terms, and consideration of the potentially positive opportunities presented by a changing climate. Addressing these research needs is necessary for generating knowledge that supports climate-affected communities in navigating the challenges and opportunities ahead.

Parker, C. (2016). Examining the vulnerability of an Inuit food system to climate change in the context of climatic and non-climatic stressors: a case study of Ulukhaktok, NT. MSc Thesis. Department of Geography, University of Guelph, Guelph, Ontario.

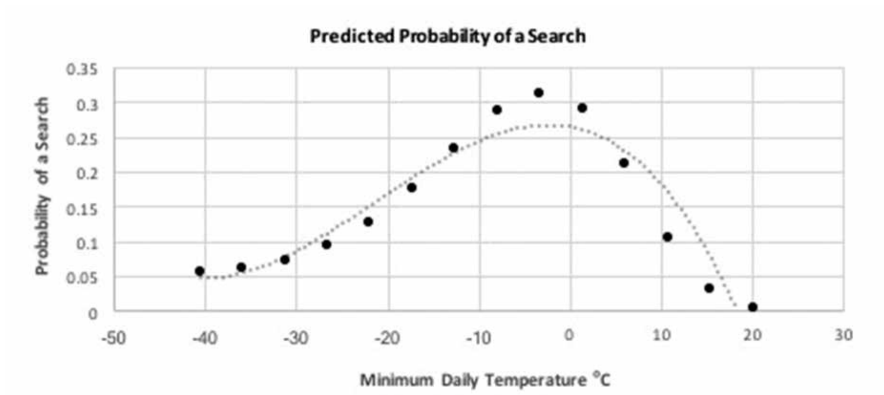

Figure 4. Predicted Probability of a Search as function of minimum daily temperature (Celsius).

This research examined the vulnerability of an Inuit food system to climate change in the context of multiple climatic and non-climatic stressors through a case study of Ulukhaktok, Northwest Territories. While other studies focus on climate change as a key stress effecting Inuit food security, this research suggests that risks associated with climate change should be considered in the broader context of other socio-economic-political stresses already effecting food security, and which condition how Inuit experience and respond to climate change.

The research shows that storage is an important determinant of food security. The finding that storage is the backbone, which supports the availability of country food is not surprising given that Inuit now live in permanent settlements and depend on cold storage facilities during summer months. Unlike most store food, access to country food is highly seasonal and harvesting activities are concentrated during the spring, summer and fall in preparation for the colder winter months. These harvesting activities coincide with the warmest time of the year when meat must be kept in cold storage until it can be moved to an outdoor location for the winter. Without a central cold storage facility in which to keep meat, harvesting is limited by how much freezer space a hunter has access to.

Some traditional sources of adaptive capacity to uphold food security are still relevant. Hunting is a dynamic activity and the success of Inuit hunters has long been linked with the ability to be flexible in the face of change. Hunters are accustomed to altering harvesting activities to accommodate changing conditions on the land, sea and ice, and changes in wildlife availability and continue to do so today under changing climatic

Table 1. Multivariable fractional polynomial regression analysis of 2013-2014 search and rescue cases in Nunavut and environmental factors.

	OR	CI-2.5%	CI-97.5%
Minimum daily temperature			
Temp 1 ((x+43.6)/10^3):	1.1684***	1.1100	1.2330
*Temp 2 ((x+43.6)/10^3)*log(x+43.6/10):*	0.9144***	0.8854	0.9427
Mean ice partial concentration	1.2150***	1.0970	1.3493
Mean ice thickness	0.9909**	0.9909	0.9977
Variety of ice types	0.6527*	0.4524	0.9232
Wind flag	1.0047	0.7082	1.4267

Table 2. Summary of 2013 and 2014 search and rescue cases in Nunavut. Data was reported by SAR organizations and collected by the National Search and Rescue Secretariat.

SAR Event	Sample Size	Percentage
Severity		
Unknown	110	54.5%
Assistance is required, but no distress exists	56	27.7%
Strong potential for loss of life	11	5.5%
Life in imminent danger	11	5.5%
Other	14	6.9%
Cause		
Unknown	118	58.4%
Mechanical breakdown	30	14.9%
Ran out of fuel	12	5.9%
Weather	6	3.0%
Medical	6	3.0%
Lost	6	3.0%
Stranded/Stuck	5	2.5%
Broke through ice	5	2.5%
Other	14	6.9%

conditions. In some cases, however, these and other sources of adaptive capacity have been compromised by societal stresses including family politics, a greater reliance on imported goods, deleterious activities (e.g. drugs, alcohol, gambling), changing levels of traditional knowledge, budgeting, and nutritional knowledge. This finding reinforces what other research has found in a food security context: addressing the non-climatic drivers of stress, while not directed at climate change or food security per se, will inadvertently enhance individual and collective adaptive capacity to deal with current and expected future risks to food security.

DISCUSSION

We continue to move forward in defining the dynamics of community vulnerability and resilience in the Inuvialuit and Nunavut regions. Through the development of new frameworks and methods of assessing shifts in vulnerability, such as utilizations of longitudinal surveys and community-based interventions, we are filling theoretical gaps and build knowledge of community and regional constraints and opportunities. Findings and developments have been widely shared with stakeholders through community workshops, strong working relationships and ongoing dialogue between research team and community partners, and Northern media coverage of our research. We have also continued to produce high quality peer-reviewed articles, with articles in CMAJ, WIREs Climate Change, and Environmental Research Letters over the past year.

There are currently two master's students, one PhD student, and an RA involved in pertinent research, these HQPs will continue to develop and produce relevant research into the 2017 grant period. Affiliated young researchers will be continuing to work with the communities of Arviat, Pangnirtung, Ulukhaktok, and Paulatuk to define aspects of community vulnerability and adaptation opportunities.

Throughout the next grant period we will be continuing to develop and implement research that examines adaptation opportunities in Northern communities. This will include exploring opportunities for the use of drones for search and rescue and further defining how social systems constrain or catalyze adaptation initiatives and policies. We will also continue to reach out to Inuit organizations and relevant government organizations, as well as draw relevant findings from the Arctic region into IPCC and UNFCCC works.

CONCLUSION

By developing new approaches to assess adaptation and vulnerability in Northern communities we are continuing to fill critical knowledge gaps for policy makers and community stakeholders. Still, gaps remain in defining how communities will be impacted by a 1.5 degree Celsius increase or as 8.5RCP suggests over a 3.0 degree increase. These questions will require further research to address the retrospective nature of past vulnerability research, working to define how social systems and non-climatic factors are shifting and implicating adaptation across the North. Over the past two years we have made headway in filling these gaps, and our planed work in 2017 (adaptation planning and further involvement with climate change policy and science networks) will continue to move us forward. Further, as we advance knowledge of community vulnerabilities to climate change in the North, we are shifting to explore the nuances of adaptation opportunities and constraints.

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FOODBORNE AND WATERBORNE DISEASE MITIGATION: COMMUNITY-BASED SURVEILLANCE FOR ENVIRONMENTAL HEALTH

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ABSTRACT

Recent research uncovered the highest rates of self-reported enteric illness (i.e., diarrhea and vomiting) reported in the world to be in Iqaluit, Nunavut, and Rigolet, Nunatsiavut. Infectious diarrhea and vomiting can be caused by contaminated drinking water (i.e., waterborne disease), contaminated food (i.e., foodborne disease), or person-toperson contact. To reduce the high rates of diarrhea and vomiting in Northern Canada, we must monitor these pathogens causing illness to understand what pathogens are responsible for illness and how people contract the illness. The goal of this project is to create a participatory, community-based monitoring system to collect information on food and water contamination, and whether or not food and water contamination is causing illness in people in Iqaluit and Rigolet, Canada. This information will be important to understand why rates of diarrhea and vomiting in these communities appear to be high. The research team will work with Northern partners to use the research results to develop potential public health response options to reduce the high rate of illness. Training is an important focus of the project. Graduate students will learn community-based approaches to research through hands-on experience with partner organizations and community members. Inuit researchers will be trained in sampling and testing food and water for pathogens that can cause food- and waterborne disease. Northern collaborators will contribute to all phases of the research design, data collection, analysis, interpretation, and results dissemination process.

KEY MESSAGES

- Foodborne and waterborne disease is a global public health priority,[1] exacerbated by climate change, shifting population dynamics, population growth, infrastructure limitations, and the globalization of travel and trade.[2–6]
- There are unique causal pathways for enteric illness in Inuit communities.
- The highest reported incidence of enteric illness in the world is in Northern Canada: incidence of enteric illness in these communities was 3x higher than national averages, and the highest in the global literature.[7]
- The end-user identified solution to the high rate of enteric illness in the North was a community-based surveillance system. As such, our project aims to create a participatory, community-based surveillance system to understand, respond to, and reduce the burden of foodborne, waterborne, and zoonotic enteric pathogens in Northern locales.
- Using participatory research methods, a series of workshops and interviews were conducted with local stakeholders and end-users to identify the items to test (i.e. brook water, clams, and dogs), and what pathogens to test for (i.e. *Cryptosporidium* and *Giardia*.
- Water Sampling and Testing: Surface water samples were collected from Sylvia Grinnell River (n=24), Apex River (n=26), and Carney Creek (n=5). Water parameters measured included date and time of collection, weather conditions, water temperature, pH, conductivity, and turbidity. Samples have been processed for isolation of *Giardia* and *Cryptosporidium* as well as the quantification of *E. coli* and total coliform indicator bacteria. Preliminary results include 20% of samples testing positive for *Giardia* and 1.8% of samples testing positive for *Cryptosporidium*.
- Pet Stool Sampling and Testing: Canine fecal samples (N=452) were collected in Iqaluit from sled dog teams, dogs from the local humane society, and fecal samples found in the environment. Of the 20 sled dogs sampled in July, 30% were positive for *Giardia* on one or more tests and 30% were positive for *Cryptosporidium* on one or more tests. During the September sampling period, 17% of dogs

were positive for *Giardia* and 22% were positive for *Cryptosporidium*. During September, we also collected 111 samples from the Humane Society and 104 environmental samples. For *Giardia*, 0.9% and 3.8% of the samples were positive from humane society samples and environmental samples, respectively, and 4.5% of both sample types were positive for *Cryptosporidium*.

- Food Sampling and Testing: In year 2, clams (N=396) were collected from local harvesters in Iqaluit. The clams were processed on-site in Iqaluit, and are currently in the laboratory at the University of California (Davis) for presence/absence testing.
- In Year 2, we:
    - » Began quantitative data collection.
    - » Trained four Inuit in environmental sampling and processing; and four graduate students.
    - » Presented 13 oral and poster presentations academic forums/conferences.
    - » Published one research article and two articles are in the late stages of peer-review.
    - » Highlighted the project in five media interviews.

OBJECTIVES

Our project aims to create a participatory, community-based surveillance system to understand, respond to, and reduce the burden of illness from foodborne and waterborne pathogens in Iqaluit.

In Year 2, we continued to pursue the objectives outlined in our proposal:

1) Establish a transdisciplinary team: We have assembled a team of transdisciplinary scholars, government representatives, and Inuit community members. Team members have expertise in the medical, veterinary, environmental science, public health, and social science fields. This team prepared the proposal, developed the study design, have began surveillance of enteric pathogens, and will continue to work together as partners through each stage of research. Our team has continued to expand and grow over the course of the project.

2) Characterize water and food systems: Understanding and respecting the social, cultural, and environmental constructs and pathways through which foodborne, waterborne, and zoonotic enteric pathogens could be transmitted is key to developing a surveillance system that respects and reflects Inuit culture, and provides the necessary information to identify and control disease. We have made great progress in examining the relationship Inuit have with food, water, and pets in the context of foodborne, waterborne, and zoonotic enteric disease.

3) Pathogen source attribution: To understand foodborne, waterborne, and zoonotic disease transmission, this project will estimate the prevalence, identify risk factors, and examine molecular source attribution of enteric pathogens in food (retail and country food), water (tap and brook water), and animals (domestic dogs, working dogs). Northern partners identified which pathogens were to be sampled and also co-developed the data collection protocols to maximize Northern research capacity development and training. We have completed one year of data collection and preliminary analysis.

4) Effective knowledge translation and extension (KTE): On-going and meaningful collaboration with Inuit stakeholders, health professionals, and Inuit organizations is essential to develop and evaluate a culturally acceptable and effective knowledge translation program to reduce foodborne, waterborne, and zoonotic enteric illness. Our end-users believe that the information that will be gleaned from this study will be critical to develop new or enhance existing public health planning, programming, and policy to effectively reduce the high reported burden of enteric illness.

KNOWLEDGE MOBILIZATION

- 10 Meetings with Federal Stakeholders: In-person meetings (n = 10 meetings) with various federal stakeholders (n = 25 people).

- 24 Meetings with Northern Stakeholders: In-person meetings (n = 24 meetings) with various Northern stakeholders (n = 25 people).
- Meetings with Northern Healthcare Professionals: We arranged several meetings with healthcare providers in Iqaluit, including physicians, primary healthcare nurses, public health nurses, and support staff.
- 10 Side Meetings at the ArcticNet Annual Scientific Meeting: We held 10 side-meetings with several Northern stakeholders and southern academics.
- Five Media Interviews: three online news articles (Ontario Veterinary College, Nunatsiaq News, and CBC North); two televised interviews (Aboriginal People's Network and CBC North).
- 13 Abstracts, conference presentations, scholarly posters: Results were shared by researchers, HQP, and Northern partners at conferences within Canada and abroad, including the annual ArcticNet Annual Scientific Meeting.
- Three Scholarly articles: one article published and two submitted to journals (under peer-review).
- One Active Website: A research website disseminates project outputs, including videos, updates on project progress, and research results.

INTRODUCTION

Foodborne and waterborne disease is a global public health priority,[1] exacerbated by climate change, shifting population dynamics, population growth, infrastructure limitations, and the globalization of travel and trade.[2–6] Endemic levels and outbreaks of enteric illness transmitted by contaminated food and water contribute to considerable morbidity, mortality, and economic costs, in particular among high risk populations.[7–14] The Public Health Agency of Canada (PHAC) describes enteric illness as a "major health concern in Canada"[15] and costs Canadians an estimated CAN $113.70 per case, which collectively costs the Canadian economy billions of dollars annually.[11,16] The cost per case in Inuit communities is likely much higher than the Canadian average considering per-capita healthcare expenditures in the North are the highest in Canada, with Nunavut having the highest cost per-capita in the world.[17] Public health agencies continue to prioritize the surveillance of enteric illness to monitor the burden of illness, detect and control outbreaks, and evaluate control measures.

Northern Canada has the highest reported incidence of enteric illness in the global peer-reviewed literature. Indigenous populations often live in substandard conditions and have reduced access to services and resources when compared to non-Indigenous citizens globally,[18–22] both of which contribute to disparities in health outcomes,[18,20,23,24] including enteric illness. Through previous research, our team found the highest incidence of self-reported enteric illness (symptomatic presentation) reported in the global literature to be in Iqaluit, Nunavut, compared to studies in other regions using the same study design and case definition. Specifically, we found enteric illness incidence in these communities was 3x higher than national averages, and the highest in the global literature.[7] In these communities, enteric illness was disproportionately under-reported in surveillance systems, compared to other regions in Canada.[7] Thus, surveillance systems, such as PHAC's National Enteric Surveillance Program, do not provide estimates of enteric illness for these communities that are suitable for comparison to other locales in Canada. It also suggests that outbreaks of foodborne and waterborne disease might not be detected by existing public health infrastructure. These surveillance challenges impact public health planning, prioritization, and response for endemic and epidemic enteric illness.

There are unique causal pathways for enteric illness in Inuit communities. Through past research, our team identified potential risk factors for enteric illness through integrated epidemiological and social science research. Many of these risk factors differ from those identified in non-Indigenous communities,[7,25–30] especially in the context of changing climates and rapid social, cultural, and economic transitions and stressors. For instance, consumption of country and retail foods, drinking untreated water, and exposure to pets were associated with increased odds of enteric illness.[7] The specific pathogens causing enteric illness and their source attribution have not previously been studied in these communities.

The end-user identified solution to the problem is a community-based surveillance system. Through proof-of-concept work, the research team and end-users identified a community-based surveillance system as an essential component for understanding, and thus reducing the high burden of enteric illness in Northern Canada. The end-users believe that a participatory, community-based surveillance system will enable a baseline understanding, enhanced response, and ultimately reduced foodborne and waterborne enteric pathogens. Importantly, the surveillance program is not the product of this research; rather, the desired outcome is to use surveillance as a tool to detect endemic and outbreak cases of illness, and understand the epidemiology of enteric illness in the North to develop response protocols; all of which are intended to reduce the burden of illness.

ACTIVITIES

Overview of Project Phases

- Phase 1) Conceptual and Methodological Development: Develop a participatory, community-based surveillance system to monitor and respond to food- and waterborne infections in Northern Canada (Year 1; completed).
- Phase 2) Data Collection and Empirical Research: Collect and analyze surveillance data.(Year 2-3).
- Phase 3) Comparative Analysis: Examine similarities and differences between communities and other locales (Year 3).
- Phase 4) Knowledge Translation and Exchange (KTE): Develop locally-appropriate and culturally-relevant knowledge translation techniques (Years 1-3).

Focus of Year 1: In Year 1, we completed our planned activities, milestones, and project deliverables, which primarily focused on Conceptual and Methodological Development (Phase 1 completed), as outlined in our proposal. At the end of Year 1 we transitioned our focus to Data Collection and Empirical Research (Phase 2).

Focus of Year 2: In Year 2, we continued work on our planned activities, milestones, and project deliverables, which primarily focused on data collection and empirical research (Phase 2), as outlined in our proposal. At the end of Year 2, our analyses are ongoing, and we will transition our focus to comparative analyses (Phase 3) in Year 3.

Collaboration and Engagement (Year 2)

- Meetings with Federal Stakeholders: We arranged several in-person meetings (n = 10 meetings) with various federal stakeholders (n = 25 people) to expand our research partnerships, refine the surveillance concept and methods, and increase matching funds. We met with representatives from:
  - Office of the Chief Scientist, Public Health Agency of Canada
  - Centre for Foodborne, Environmental and Zoonotic Infectious Diseases, Public Health Agency of Canada
  - FoodNet Canada, Public Health Agency of Canada
  - National Microbiology Laboratory, Public Health Agency of Canada
  - Laboratory for Foodborne Zoonoses, Public Health Agency of Canada
  - Strategic Policy, Planning and International Affairs Branch, Public Health Agency of Canada
  - Indigenous and Northern Affairs Canada

- Meetings with Northern Stakeholders: We arranged several in-person meetings (n = 24 meetings) with various Northern stakeholders (n = 25 people) to expand our research partnerships, refine the surveillance concept and methods, and increase matching funds. To promote meaningful and strong Northern engagement in research design, we met with each stakeholder four times (June, July, September, and November), including representatives from:
    - » Nunavut Research Institute
    - » Department of Health, Government of Nunavut
    - » Nunavut Climate Change Centre
    - » Qaujigiartiit Health Research Centre
    - » Iqaluit Public Health
    - » Nunavut Tunngavik Inc.
- Meetings with Northern Healthcare Professionals: We arranged several meetings with healthcare providers in Iqaluit, including physicians, primary healthcare nurses, public health nurses, and support staff.
- Side Meetings at the ArcticNet Annual Scientific Meeting: We held 10 side-meetings with several Northern stakeholders and southern academics to build research synergies, grow partnerships, and develop our surveillance concept. These were formal meetings; as such, the project manager followed-up with each stakeholder via email and circulated meeting notes.
- Outcome: Through meaningful collaboration with our Northern partners, we developed and finalized the surveillance concept, methodologies, and methods.

Qualitative Data Collection (Year 2)

In year 1, an ethnographic study design[31] was used to follow a cohort of families (n = 10 families). Three separate interviews were conducted per family, resulting in a total of 30 in-depth interviews. Families were purposively selected based on a maximum variation strategy. In Year 2, we began to analyse these data.

Quantitative Data Collection (Year 2)

- In consultation with Northern stakeholders, the quantitative research questions, study design, and data collection procedures were developed.
- Data collection began in June 2016.
- Canine Stool Sampling and Testing: High caliber graduate students collected the data and are conducting analyses (PhD Candidate: Dr. Danielle Julien (DVM, MPH). Data collection took place in July and September 2015. Canine fecal samples (N=452) were collected in Iqaluit from sled dog teams, dogs from the local humane society, and fecal samples found in the environment. Samples were tested for the presence/absence of *Giardia* cysts and *Cryptosporidium* oocysts on-site. Next steps involve molecular characterization of positive samples to detect parasite species; this will begin in February 2017.
- Clam Sampling and Testing: MSc Candidate, Anna Manore, is examining enteric pathogens in locally harvested clams. In Year 2, clams (N=396) were collected from local harvesters in Iqaluit. Samples were processed to retrieve hemolymph and digestive gland fluid on-site. Anna is at the University of California Davis for the winter semester (January-April 2017) analyzing clam samples under supervision of Dr. Karen Shapiro. Samples are undergoing standard detection methods and molecular analysis to provide an estimate of the prevalence of *Giardia* and *Cryptosporidium*. Next steps involve completing lab work, performing descriptive statistics, and conducting comparative analysis of samples.
- Water Sampling and Testing: MSc Candidate, Stephanie Masina, worked closely with Jamal Shirley (Nunavut Research Institute) to examine waterborne pathogens in surface water in

Iqaluit. Stephanie's data collection took place between June 29th and September 28th 2016. Surface water samples were collected from Sylvia Grinnell River (n=24), Apex River (n=26), and Carney Creek (n=5). Additional data collected included date and time of collection, weather conditions, water temperature, pH, conductivity, and turbidity. Samples have been processed for isolation of *Giardia* and *Cryptosporidium* as well as the quantification of *E. coli* and total coliform indicator bacteria. Preliminary results include prevalence estimates of *Giardia*, *Cryptosporidium*, and indicator bacteria from the collected samples. Molecular genotyping and further laboratory analysis will begin in April 2017. Analysis is anticipated to be complete by August 2017.

Communications (Year 2)

Media engagement

- Three online news articles (Ontario Veterinary College, Nunatsiaq News, and CBC North).
- Two televised interviews (Aboriginal People's Network and CBC North).

Abstracts, conference presentations, scholarly posters: Results were shared by researchers, HQP, and Northern partners at conferences within Canada and abroad, including the annual ArcticNet Annual Scientific Meeting. See publication list for details.

Scholarly articles: one article published and two submitted to journals (under peer-review).

Active Website: A research website disseminates project outputs, including videos, updates on project progress, and research results.

Training and Development: HQP training in community-based research methods, data collection and analysis, and communications.

Matching Funds (Year 2)

In Year 2 we secured additional matching funds, leveraging over three-times the funds received from ArcticNet NCE. We have also secured substantial additional funds (to start in Year 3) from governments to conduct additional laboratory testing on our samples collected in Year 2, as well as the samples to be collected in Year 3.

RESULTS

We have selected key results from our ArcticNet funded work during Year 2.

A community-based foodborne, waterborne, and zoonotic enteric disease surveillance plan was implemented. In 2016 we began data collection to monitor and characterize *Giardia* and *Cryptosporidium* in Iqaluit; these pathogens were chosen based on extensive stakeholder engagement and consultation. Additionally, we wanted to ensure that the sampling and testing protocol matched national surveillance efforts (e.g. FoodNet Canada) to aid in data sharing and comparability. Using a systems approach, we monitored these two parasites in food, water, and dogs, and are collaborating with Drs. Goldfarb and Yansouni to monitor these parasites in humans. While we are focusing on these two parasites in this project, we will store samples for future testing of other pathogens when funds become available. While a number of pathogens and environmental exposures were considered, based on extensive stakeholder engagement, our surveillance program involves the following:

Prevalence of Positive Samples

- Pets: There were 60 samples collected from 20 dogs during the July pilot test (one sample per dog on three consecutive days) and 177 samples from 59 sled dogs during September. Dogs were considered positive if at least one sample was positive on at least one of the tests. Of the 20 sled dogs sampled in July, 30% were positive for *Giardia* on one or more tests and 30% were positive for *Cryptosporidium* on one or more tests. During the September sampling period, 17% of dogs were positive for Giardia and 22% were positive for *Cryptosporidium*. During September, we also collected 111 samples from the Humane Society and 104 environmental samples. For *Giardia*, 0.9% and 3.8% of the samples were positive from humane society samples and environmental samples, respectively, and 4.5% of both sample types were positive for *Cryptosporidium*.

- Food: Clams were collected; laboratory work is currently in progress.
- Water: Preliminary results include 20% of samples testing positive for *Giardia* and 1.8% of samples testing positive for *Cryptosporidium* (n=55).

Source Attribution

- All samples (dog stools, clams, and water) are currently undergoing molecular source attribution.

DISCUSSION

Enteric illness in the Arctic. The team's previous research found that the rate of enteric illness in the Arctic was the highest reported in the world. With ArcticNet funding, an MSc student further examined these data and found that there were no significant differences in odds of illness between Inuit and non-Inuit people in Iqaluit. The reason for this finding is unclear, and the pathogen testing in Year 2 was intended to test several hypotheses. Stakeholder concern about *Giardia* and *Cryptosporidium* was supported by literature that suggests the prevalence of these pathogens in the Arctic is higher than other southern locales.[32]

Foodborne disease. Hunting, trapping, fishing, gathering, and sharing country food are still practiced in Iqaluit, and are important aspects of Inuit livelihoods, health, and wellbeing.[33] Studies suggest that some factors related to country and retail food increased the odds of enteric illness.[29,34–37] The routes of contamination, as well as preparation methods for country and retail meat in the North are different than retail meats available for purchase, and these transmission pathways are not well understood. Through extensive stakeholder engagement, we decided to focus on locally harvested clams, as stakeholders ranked clams as an important source of enteric infection. This focus on clams is supported by previous pilot research in Nunavik that suggests clams are a source of *Cryptosporidium* infection in humans.[39]

Waterborne disease. Several Inuit communities face water-related challenges, including provision of safe municipal drinking water,[40] effects of climate change and high impact weather events on drinking water safety,[41,42] and the preference of many residents to seek alternative drinking water sources including brooks, streams, ice, and snow.[40] Drinking water has been identified as a source of enteric illness in past research in the North;[35,37,41] however, source attribution of pathogens has been rarely conducted for parasites. As such, focusing our water sampling on *Cryptosporidium* and *Giardia* will contribute to limited literature, and increase our understanding of waterborne risks in the Arctic. Furthermore, considering the relatively limited media coverage of Arctic water security, in Year 2 we actively engaged with the media to bring attention to water security challenges in the Canadian North.

Zoonotic enteric infection. Stakeholder concern about dogs as a source of enteric infection is supported by previous research that identified puppies as an important risk factor for enteric illness in the Arctic[37] and elsewhere in Canada.[8–10,16,43] Indeed, dogs are known to asymptomatically carry several pathogens that could cause enteric illness in humans.[44–46] Our stakeholders also hypothesize that pathogen loads in dogs in the North differ from the South. For example, *Giardia* parasites are grouped within distinct assemblages, some of which are species-specific and some of which infect multiple species. In southern populations, dogs almost always carry dog-specific *Giardia* assemblages and human disease is unrelated. In some Canadian First Nations, however, some scholarly evidence suggests that this may not be the case.[47] In communities with wastewater treatment infrastructure challenges, human assemblages of *Giardia* are common in dogs because they are exposed to human sewage.[47] As such, dogs are a potential source of human infection, and vice versa. Our end-users believe that this type of unusual pathogen source attribution might also be true in Northern Canada. Therefore, monitoring dogs for fecal shedding of *Cryptosporidium* and *Giardia* will help us to understand whether dogs are reservoirs of these zoonotic pathogens in Iqaluit.

CONCLUSION

We have successfully designed and implemented a foodborne, waterborne, and zoonotic enteric illness surveillance system in collaboration with Northern stakeholders. Our surveillance design is grounded in scientific evidence and Inuit traditional knowledge, will provide data that are comparable to national surveillance programs, and is culturally appropriate and locally relevant. We are ending Year 2 on schedule. Data collection is on-going and analysis is underway. We have completed Year 2 project milestones and deliverables (as outlined in our proposal) including quantitative data collection.

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WILDLIFE DISEASES IMPORTANT FOR HUMAN HEALTH AND FOOD SAFETY IN THE CHANGING ENVIRONMENT OF THE EASTERN SUBARCTIC

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ABSTRACT

The proposed project integrates traditional knowledge from communities in Nunavik and Nunatsiavut with a combination of disciplines (epidemiology, microbiology, population genetics, behavioural ecology, landscape ecology, disease modelling, and anthropology) which will help to better assess and predict the risk of exposure to diseases relevant to the health of wildlife and local communities. We will target a directly transmitted viral zoonosis (rabies) and two food borne parasites (*Trichinella* and *Toxoplasma*) with known potential to negatively impact human and animal health in the North. We will also work with communities and Hunter/Trapper Organizations (HTOs) to identify their concerns, which may highlight other priorities. Results will be shared with collaborators (an array of public health personnel and policy makers), participating communities (through environmental health officers, annual presentation to HTOs), and high risk populations for exposure (e.g. school children) through educational outreach programs.This project will provide baseline information that communities, public health personnel, wildlife managers, and policy makers can use to determine the role of wildlife in human exposure to zoonoses (and vice versa), and to develop culturally appropriate control and surveillance strategies for diseases affecting the health of both wildlife and people in the Canadian Eastern Subarctic.

KEY MESSAGES

- Wildlife are an important source of food and income in northern communities, but are also a source of human exposure to diseases.
- Rapid climate warming across the Canadian Arctic is driving rapid ecosystem change, with a potential impact on the ecology of wildlife diseases and human exposure to these diseases.
- Our project aims to assess the current health risks presented by wildlife diseases for communities in the Eastern Subarctic through community consultation and testing for diseases in hunted wildlife, and to estimate the impact of rapid regional climate change on these health risks through statistical analyses and modelling.
- Toxoplasmosis is an important parasitic disease in people in Nunavik. Since the parasite can be acquired through food-borne routes, our project is monitoring harvested wildlife in three Nunavik communities for toxoplasmosis, focusing on wildlife species suspected to be involved in transmission. Results from Year 2 showed that *Toxoplasma* and another foodborne parasite, *Trichinella*, are present within terrestrial wildlife in Southwestern Nunavik. Neither parasite was present in samples from ringed seal and ptarmigan. Inuit exposure to *Toxoplasma* is possible through processing of fox carcasses and consumption of Canada geese. Other possible sources will be explored in Year 3.
- Rabies is a lethal disease with regular outbreaks in arctic and red (coloured) fox populations posing a threat to the health of dogs and people; Year 2 monitoring results suggest that fox populations reached the low point of their multi-annual population cycle in 2015-2016, with correspondingly little rabies activity in the population, but fox numbers are on the rise in 2017. Genetic data point to several distinct subpopulations in Nunavik-Nunatsiavut.
- People acquire wildlife diseases through direct contact with wildlife, but also indirectly from domestic dogs that contact wildlife; our project is working in partnership with the community of Kuujjuaq to carry out community consultations and monitor human-dog-wildlife interactions in order to better understand the routes and risks of human and dog exposure to wildlife disease. Year 2 results show that Kuujjuaq dogs are in regular contact with a variety of wildlife species, with about 10% of dogs having documented inter-actions with foxes. We also detected potentially

zoonotic parasites (*Giardia* and *Cryptosporidium*) in fecal samples from dogs in Kuujjuaq, but genetic results are still pending to determine if these are the zoonotic types. Trail cameras and visual censuses suggest that dogs are present throughout the village but that wildlife contacts occur primarily on the edge of town and near key locations (e.g. the municipal landfill).

- Climate warming is altering wildlife ecology, including where and when parasites are transmitted and wildlife disease outbreaks occur; our project is combining cutting-edge models of wildlife disease epidemiology with state-of-the-art climate projections for the Eastern Subarctic to predict how human exposure to food-borne parasites (*Toxoplasma* and *Trichinella*) and viruses (rabies) is likely to change in the coming years. In Year 2 we identified climate-sensitive parameters affecting persistence of *Toxoplasma* oocysts in the terrestrial environment, and further developed the Arctic Rabies Model simulation platform to incorporate spatial ecology of foxes and improve model predictions.

OBJECTIVES

In 2016-2017, we addressed the following objectives as laid out at the beginning of the project:

1. Detect and characterize diseases in wildlife populations with close contact with human settlements at a broad regional scale.
2. Better characterize the human/wildlife interface by assessing contact rates and potential routes of exposure between people and wildlife at the individual community level.
3. Develop models to identify important risk factors for wildlife and human exposure, to predict future disease risk for people and wildlife within a changing climate, and to evaluate options for risk management.

KNOWLEDGE MOBILIZATION

- 30 presentations at scientific conferences.
- Presentation of results at the Nunavik Research Center (NRC) at end of field season (Summer 2016). This is the first time any research group has done that and it was highly appreciated. The presentation was then distributed throughout the community by NRC.
- Interactions between students (MC Frenette and H Déry) and locals through participation in community activities (e.g. weekly painting workshops) where they had an opportunity to talk casually with people about their work (Summer 2016).
- Knowledge dissemination through project Facebook pages (Kuujjuaq foxes, Kuujjuaq dogs).
- Summer camp activities on dogs and foxes organized in Kuujjuaq (Summer 2016).
- Training for high school student interns through NRC in Kuujjuaq (Summer 2016) – concrete example of applied science, and strong link to community through personal contacts of students.
- Several collaborators (including one from Kuujjuaq) participated in a World Café discussion on ethical principles for the conduct of research in the North (one-day workshop in Saint Hyacinthe, April 2016).
- Organization of a webconference on health iniquities in Aboriginal populations in Canada for all ArcticNet collaborators and students (April 2016).
- Presentation of the sub-projects on dogs, foxes and rabies to representatives of the Cree Regional Authority, Makivik Corporation (Inuit), the Naskapi Landholding Corporation, as well as Quebec and Canadian Governments at the Hunting, Fishing, and Trapping Coordinating Committee meeting in Mistissini (HFTCC) (June 2016).

- Results sharing on the wildlife sampling to all 14 Nunavik RNUK representatives during their annual meeting (November 2016) held in Salluit.
- Results sharing at conference call with Nunavik Regional Nutrition and Health Committee (Nov 2016).
- Participation of community coordinator from Inukjuak at the ASM in Dec 2016.
- Joint development of pamphlet regarding human health implications of toxoplasmosis findings in wildlife with Nunavik Regional Nutrition and Health Committee, Health Canada, and Public Health Agency of Canada (ongoing).

INTRODUCTION

Wildlife is valued for cultural, nutritional, economic, and ecological reasons in northern communities across Canada (Chan et al. 2006). Although harvested wildlife represents an important source of food security, it may also be a source of human exposure to zoonoses (diseases that transmit between animals and people) (Cutler 2010). In addition, frequent interaction with wildlife in northern communities increases the risk of direct transmission of zoonotic diseases such as rabies from infected wildlife to domestic animals and people. Climate warming is a particularly important driver of ecosystem change in the Arctic, along with anthropogenic activities such as increasing shipping activity, resource development, and increasing human and companion animal populations (Cramer & Yohe 2014). The primary objective of our project is to better understand the current health risks presented by wildlife diseases such as rabies, toxoplasmosis and trichinellosis in Arctic communities, and how these are likely change over time in a rapidly warming climate.

Our project specifically addresses gaps in our understanding of the ecology and transmission dynamics of wildlife diseases of public health importance in order to understand: 1) how zoonoses are transmitted amongst wildlife and how people are exposed, 2) how wildlife, domesticated animals and people interact in a changing environment, 3) how diseases spread from north to south (i.e. arctic fox rabies) and from south to north (such as toxoplasmosis), and 4) how disease transmission may be affected by a warming, more climatically variable, and more interconnected Arctic.

In Year 1 (2015-2016), we established four thematic working groups, each with a coordinator: 1) Food safety, 2) Fox genetics and rabies, 3) People, dogs and wildlife, and 4) Climate and disease modeling. Within these four working groups, our team made significant progress toward each of our project objectives by establishing a wildlife disease monitoring network, building trust and collaborations with partner communities and aligning research goals with local needs through community consultation, and gathering the necessary information and refining tools to carry out climate-coupled disease modelling.

ACTIVITIES

Project activities for Year 2 (2016-2017) were focused around intensive collection of samples from harvested and trapped wildlife, laboratory analyses to establish baseline information on disease prevalence and genetic data, collecting community data and traditional knowledge through interviews, surveys and informal discussions with people in communities, and communication activities to share research plans and outcomes with communities as well as among collaborators within our research project.

In this second year of the project, several key activities helped to coordinate communication, resource use, and HQP supervision. In April 2016, we held a one day in-person project meeting and workshop in Saint-Hyacinthe, with remote participants connected by webconference, and we are in the process of organizing a second edition that will take place in May 2017.

In addition, we have continued to maintain regular communication through video-conferenced project meetings at key points in the year and in-person interactions at the Arc-ticNet ASM.

1) Food safety

The focus of Year 2 was to validate and apply best-available laboratory tests for these two important foodborne parasites (*Toxoplasma* and *Trichinella*) in harvested wildlife in Nunavik, and we are pleased to report considerable success this year (Table 1).

2) Fox genetics and rabies

We made significant progress in a) field collection of trapped fox, b) lab processing of the fox carcasses, and c) genetic analyses for collected fox samples:

a. For Year 2, full-scale sampling is continuing in fall 2016 in the four communities of Nunavik (Kuujjuaq, Puvirnituq, Kuujjuarapik, and Inukjuak), five communities of Nunatsiavut and southern Labrador (Happy Valley-Goose Bay, Hopedale, Labrador City, Makkovik, and Nain), and five communities of James Bay (Chissasibi, Wemindji, Waskaganish, Waswanipi, and Mistissini). In addition, we extended fox sampling activities to the Côte-Nord region, further covering the suspected pathways of rabies spread from Nunavik to southern Quebec.

At the Annual HTO Meeting in November 2016, we were invited to provide a progress re-port on the fox sampling to all 14 Nunavik HTO representatives. Overall, participating communities were happy with the project and curious about any results obtained so far.

b. All the fox carcasses collected in Year 1 have been processed at the Centre québécois sur la santé des animaux sauvages (CQSAS) in Saint-Hyacinthe and the samples were distributed among the different research organizations for genetic and disease analyses. The carcasses collected in Kuujjuaq have been sub-sampled at the Nunavik Research Center (NRC) by MSc students H. Déry and MC Frenette. Rabies testing was carried out at CQSAS on the samples from Nunavik collected in Year 1.

c. Nine-locus microsatellite profiles had been obtained for 140 arctic and 146 coloured foxes from throughout northern Canada in Year 1 (samples collected 2011-2013; see Table 2 line 1). In Year 2, MSc student Thaneah Alanazi continued to obtain microsatellite genetic profiles for fine-scale population structure estimates focused in Quebec and Labrador. First, additional samples that had been collected pre-project from northern Quebec and southern Labrador were analyzed for the original nine loci reported in Year 1. This included N=36 from Kuuijuaq, N=11 from Port Hope Simpson, and N=36 from Happy-Valley Goose Bay and Labrador City area (samples collected 2013-2015; see Table 2 lines 2-4). For the Eastern Subarctic focus, we also obtained data for an additional five microsatellite loci for 132 of the pre-project (90 coloured and 42 arctic collected 2011-2013; see Table 2 line 1); the remainder of these samples are currently being processed. Additional samples from southern Quebec (N=90, collected 2012-2014) and Nunavik, James Bay, and Abitibi (N=180, collected 2014-2015 and during Year 1 2015-2016) are expected shortly, and 14-locus profiles for all remaining samples will be completed; much if not all of this should be done within the Year 2 reporting period.

A sequence database of 204 isolates of the arctic fox strain of rabies virus collected in Canada, Alaska and Greenland has been compiled. This includes 126 samples for which whole genome sequence has been obtained, with the remaining isolates partially characterised at the N and/or G gene loci. A collaborative manuscript for the combined rabies host genetics and viral genetics is in preparation (Table 2) (Table 3).

3) People, dogs and wildlife

a. Kuujjuaq Dog Survey: data analysis completed; results shared with the community in April 2016.

Table 1. Laboratory tests for these two important foodborne parasites (Toxoplasma and Trichinella) in harvested wildlife in Nunavik.

SUMMARY OF ACTIVITIES	LOCATION	DATE
DNA extraction and real-time PCR validation	Saskatoon, SK	Jan – May 2016
Serology (450 animals) and real-time PCR testing (1100 samples)*	Saskatoon, SK	June – Dec 2016
Spring geese samples (85) received from Nunavik	Saskatoon, SK	June 2016
Fox samples (32) received from Nunavik	Saskatoon, SK	Aug – Nov 2016
DNA extractions and PCR testing (from 2016)	Saskatoon, SK	Sept 2016 – Jan 2017
Trichinella testing (seals and foxes)	Saskatoon, SK	Sept – Dec 2016
PhD student Emilie Bouchard starts: trapper recruitment	Saskatoon, SK	Sept – Dec 2016
Teleconference Nunavik Nutrition Health Committee	SK/QC	Nov 2016
Annual Nunavik RNUK meeting (3rd one attended)	Salluit, QC	Nov 14-19, 2016
ArcticNet ASM Conference	Winnipeg, MB	Dec 5-9, 2016

*1100 tissues from Ringed seals (61), Canada geese (156), ptarmigan (166), foxes (39) and caribou (31) collected in 2015

Table 2. Fox samples collected between year 2011 and 2015.

Samples	Collected	Received	Status of Genetic Data Collection
140 arctic and 146 coloured foxes; across northern Canada – includes 47 arctic and 11 coloured foxes from Quebec and Labrador	2011-2013	Various times during 2013	mitochondrial control region completed pre-project; 9 microsatellite loci analyzed in Year 1; 5 additional loci completed for Quebec and Labrador samples in Year 2
36 Kuujjuaq, QC foxes; 18 coloured and 18 arctic	2013-2014	May 2014	14 microsatellite loci completed in Year 2
Port Hope Simpson, Labrador coloured foxes N=11	2013	January 2015	14 microsatellite loci completed in Year 2
Happy Valley-Goose Bay and Labrador City, Labrador coloured foxes N=36	2014-2015	December 2016	14 microsatellite loci completed in Year 2
Southern QC, N=90	2012-2014	Expected January 2016	Partial completion of 14-locus profiles in Year2
Nunavik, James Bay, and Abitibi, QC N=180	2014-2015 and Year 1	Expected January 2016	Partial completion of 14-locus profiles in Year2

In November 2015, we undertook a survey of dog owners in Kuujjuaq, including mushers. The survey characterized dog demographics, health, feeding, housing, relationship with wildlife as well as perceptions about dogs. In 2016, data analysis was completed and the results were released in April 2016 in the Kuujjuaq community by radio news, three posters and a report available through the web.

b. Census of dogs (attached free-roaming), spatio-temporal activities and cohort study: pilot in Kuujjuaq - June-July 2016.

In Kuujjuaq, the largest community in Nunavik, dogs are ubiquitous and form an integral part of the community; however, the degree to which Kuujjuaq dogs are affected by parasites, and their potential for transmitting zoonotic parasites to people, remains poorly documented. The objectives of the study of MSc student Hélène Déry were to: 1) characterize the Kuujjuaq dog population in terms of demographics and spatial/temporal patterns of activity, 2) measure the prevalence of gastrointestinal parasites in a cohort of Kuujjuaq dogs, and 3) determine which factors

Table 3. Summary, location and dates of activities for the current year.

SUMMARY OF ACTIVITIES	LOCATION	DATE
Genetic analysis of fox samples	St. John's, NL	May 2016 – March 2017
Lab processing of fox carcasses of Year 1	Saint-Hyacinthe, QC/Kuujjuaq, Nunavik	June – Nov 2016
Rabies testing of fox carcasses of Year 1	Saint-Hyacinthe, QC	July 2016
Hunting, Fishing and Trapping Coordinating Committee meeting (HFTCC)	Mistissini, QC	June 9 2016
Preparation of sampling kits	Quebec, Qc	August 2016
Fox field collection Year 2	Nunavik/Labrador/ James Bay/Côte Nord of QC	Oct. 2016 – Apr 2017
Annual Nunavik RNUK meeting (3rd one attended)	Salluit, QC	Nov 14-19, 2016
Genetic analysis of fox samples of Year 1	St. John's, NL	May 2016 – March 2017

influence the prevalence of gastrointestinal parasitism in Kuujjuaq dogs. We performed fecal flotation for helminth and coccidian parasites and a commercial immunofluorescent antibody test for *Giardia* and *Cryptosporidium* on 34 samples of dog feces collected from known animals (cohort) and the environment.

In order to document the spatial and temporal distribution of attached and free-roaming dogs, H. Déry carried out 12 visual censuses from May-August 2016. During each census, all roads in the village were surveyed systematically by car, all attached and free-roaming dogs were counted, and their locations noted.

c. Dog and wildlife contact: pilot camera trap study in Kuujjuaq - June-July 2016.

The objectives of MSc student Marie-Christine Frenette's project are 1) to characterize the possible interactions between foxes, the primary reservoir for Arctic rabies, and dogs in northern communities, and 2) to gain a better understanding of people's knowledge and perception of rabies in Nunavik. To do so, the spatial distribution of foxes and dogs around two communities, Kuujjuaq and Inukjuaq, will be quantified using a network of trail cameras active for 1-2 months, twice a year (summer and winter). In summer 2016, 34 cameras were installed in a spatial grid surrounding Kuujjuaq, and activated for one month to detect the presence and relative abundance of wildlife near the community in summer.

d. Mapping all dog-related issues in Kuujjuaq: final map (October 2016).

e. Co-Building of a Multi-Criteria Decision Analysis (MCDA) tool to inform the Kuujjuaq Dog Program to mitigate important dog-related issues in Kuujjuaq: October 2016 (Table 4).

4) Climate and disease modelling

In Year 2, we developed a model of *Toxoplasma* dynamics as part of the Masters project of Mathilde Mercat at Université de Rennes cosupervised at Université de Montréal (completed). This project comprised a modelling study to i) increase our understanding of the dynamics of transmission of *Toxoplasma gondii* in the north; and ii) produce hypotheses for effects of climate change on the abundance of *T. gondii* in transmission cycles and the dispersion of *T. gondii* into the Arctic environment. The modelling method comprised the integration of a predator-prey (lynx-snowshoe hare) model (lynx being the likely main definitive host for *T. gondii* and hare being the main prey for lynx and likely intermediate hosts) with a Susceptible-Infected-Recovered (SIR) pathogen transmission model that included dynamics of *T. gondii* oocyst survival in the environment. A publication is now in preparation (see below). Ongoing toxoplasmosis modelling will be carried out as part of the PhD project of Emilie Bouchard.

The activities for the research projects on modelling rabies among red foxes in Southern Ontario (to validate the adaptation of the rabies model to foxes – this work was started in Year 1) and in Arctic foxes in the North were focused on:

a. Improving the movement process of simulated foxes in the Ontario Rabies Model (ORM) and Arctic Rabies Model (ARM). Animal movement has important repercussions for transmission and spread of infectious diseases (Fèvre et al. 2006). To incorporate ecological realism in the ORM and ARM, we needed to identify broad-scale movement strategies used by red foxes and Arctic foxes to find resources. Based on popular approaches using net squared displacement (Bunnefeld et al. 2011, Bastille-Rousseau et al. 2016) for distinguishing between different animal movement modes at large scales (i.e., home-range, nomadic behavior, dispersal, and migration), we analyzed Arctic fox movement based on satellite-tracking data and simulated all movement types observed in individuals from random walk data. The satellite-tracking data were provided by the research team of Pr. Dominique Berteaux (Université du Québec at Rimouski) and collected on Bylot Island, Nunavut, Canada. The models used to simulate the different movement modes will be incorporated into the ORM and ARM assuming that red fox movement is also characterized by such modes (Phillips et al. 1972).

b. Improving the epidemiological processes linked to incubation and infectious periods, and transmission coefficient in the ORM and ARM. In particular, we added stochasticity in the modelling of incubation and infectious periods by using the Erlang theoretical distribution. This distribution gives a good approximation of real incubation and infectious period distributions (Hampson et al. 2009, Krylova and Earn 2013). In addition, we modified the modelling of transmission coefficient by including one parameter for duration of contacts between individuals. This parameter is relevant to rabies transmission and will be simulated from the log-

Table 4. Summary, location and dates of activities for the years 2015-2016.

SUMMARY OF ACTIVITIES	LOCATION	DATE
Kuujjuaq Dog Survey result dissemination	Kuujjuaq	April 2016
Dog pilot study	Kuujjuaq	June – July 2016
Camera trap pilot study	Kuujjuaq	June – July 2016
MSc Student recruited at UdeM	Saint-Hyacinthe, QC	
Map of all dog-related issues in Kuujjjuaq	Kuujjuaq	October 2016
Co-building and MCDA tool	Kuujjuaq	Oct 2016 – March 2017
Finding dissemination at the Inuit Congress	St-John's, NL	October 2016
Finding dissemination at the international One Health & Ecohealth congress	Melbourne Australia	December 2016

Table 5. Summary and dates of activities in St-Hyacinthe in 2016-2017.

SUMMARY OF ACTIVITIES	LOCATION	DATE
Masters on Toxoplasmosis modelling completed	St-Hyacinthe, QC	October 2016
Analyses of red fox rabies data in Southern Ontario	St-Hyacinthe, QC	November 2016
Building movement models for Arctic foxes	St-Hyacinthe, QC	Nov – Dec. 2016
Updating the parameters in ORM	St-Hyacinthe, QC	January 2017
Updating the parameters in ARM	St-Hyacinthe, QC	January 2017
Updating the landscape in ARM	St-Hyacinthe, QC	January 2017
PhD recruited	St-Hyacinthe, QC	January 2017

normal theoretical distribution (Reynolds et al. 2015, Hirsch et al. 2016).

c. A PhD student has being recruited (Agathe Allibert) to expand the ARM to simulate the spread of rabies in the two species of foxes in the context of climate and anthropogenic changes, integrating data on population dynamics and movement behaviour, rabies surveillance data and regional climate model data. In addition, the student will also participate in knowledge transfer of modeling results to public health stakeholders and communities in Northern Canada in order to improve Arctic fox rabies management and protect the health of northern communities. (Table 5).

RESULTS

1) Food safety

a. Number of wildlife sampling kits received between 2015-2016: > 425 animals (Table 6)
b. Serology: > 450 analyses (Table 7)
c. DNA Extractions performed by species and tissues: > 1,100 tissue extractions (Table 8)
d. PCR analyses: > 1,100 reactions (Table 9)
e. Trichinella testing (tongue)

In March 2016, there was an outbreak of trichinellosis in people in Nunavik that was initially linked to consumption of seal meat. Although we did test some seal meat implicated in the outbreak, sample quality was such that our results were inconclusive. However, the parasite was not detected in tongues from 61 ringed seals harvested during this time period (Table 10).

2) Fox genetics and rabies

a. Trapped foxes collected in winter 2016-2017 (Table 11).
b. The rabies virus was not detected in any analyzed brain samples of foxes collected in Nunavik during the winter 2015-2016 (N=39).
c. Clustering analysis of 90 coloured fox samples from five sampling locations using the software STRUCTURE identified three distinct genetic clusters and allocated individuals within localities to clusters as shown in (Figure 1). Individuals from three locations (North West River, Labrador West, and Kuuijuaq) tended to cluster together, while the remaining two (Port Hope Simpson and Cartwright) were genetically distinct.
d. Phylogenetic analysis of 204 isolates of the arctic fox strain of rabies virus identifies several variants of the Arctic three lineage responsible for most rabies cases across Northern Canada in recent years. Further phylogeographic analysis is ongoing to explore correlation between rabies virus variant spread and fox population structure.

3) People, dogs and wildlife

a. Findings of the 2016 Kuujjuaq Dog Survey relevant to the dog-wildlife contact

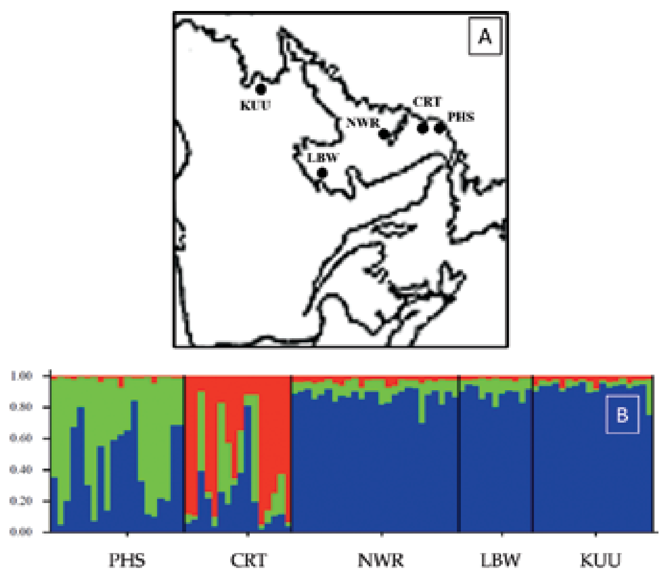

Figure 1. Analysis of 14-locus microsatellite from 90 coloured foxes from five sampling locations. A. Schematic of the Quebec and Labrador study area showing the five localities B. Structure plot indicating individual membership to each of three genetic clusters, according to sampling location. PHS= Port-Hope-Simpson; CRT=Cartwright; NWR=North West River; LBW = Labrador West; KUU= Kuujjuaq.

Interactions (to play, chase or fight) with other dogs were reported by 87% of respondents and mostly everyday (52% of this subgroup). Interactions with raven were also frequently reported (52% of respondents, every day for 42% of this subgroup). Interactions with porcupines were observed by 19% of respondents, but this was one unique, shared event for most respondents. Interactions of dogs with foxes, bear or wolves were reported rarely (Table 12, Figure 2).

b. Results of 2016 census of dogs and cohort study in Kuujjuaq.

Table 6. Number of wildlife sampling kits received between 2015-2016.

Community:	Seals	Geese	Ptarmigan	Foxes
Kuujjuaraapik	18	51	104	12
Inukjuak	41	85	71	11
Puvirnituq	2	20	17	9
Kuujjuaq	--	--	--	7
TOTAL	**61**	**156**	**186**	**39**
*Total # of kits returned: **442**				

Table 7. Serology analysis performed by species.

Species	# analysed	Pos	Neg	Prop Pos(%)
Seals - MAT	61	12	49	**19.7%**
Seals – MAT (w/ lipid removal)	61	0	61	**0%**
Seals – ELISA	61	20	41	**32.7%**
Canada Geese - MAT	156	16	140	**10.2%**
Ptarmigan - MAT	165	0	165	**0%**
Caribou - MAT	31	7	24	**22.6%**
Fox - MAT	39	15	24	**38.5%**
TOTAL	**452**	**58**	**394**	**12.8%**

Table 8. DNA analysis performed by species and tissues.

Species	Liver	Heart	Muscle	Brain	Gizzard	# of extractions
Seal	61	61	61	-	-	**183**
Geese	42	156*	30	156*	72	**456**
Ptarmigan	-	165*	-	165*	-	**330**
Fox	-	39	-	39	-	**78**
Caribou		31		31		**62**
Total	**103**	**452**	**91**	**391**	**72**	**1109**
*Geese brains in pools of 4; Ptarmigan brains in pools of 5						

Table 9. PCR analyses per species.

Species (n)	Liver	Heart	Muscle	Brain	Gizzard	# Pos animals	Prop Pos (%)
Seal (61)	0	0	0	-	-	**0**	**0%**
Canada Goose (151)*	1	9	2	9	1	**13**	**8.6%**
Ptarmigan (165)	-	0	-	0	-	**0**	**0%**
Caribou (18)	-	0	0	0	-	**0**	**0%**
Fox (39)	-	16	-	9	-	**19**	**48.7%**

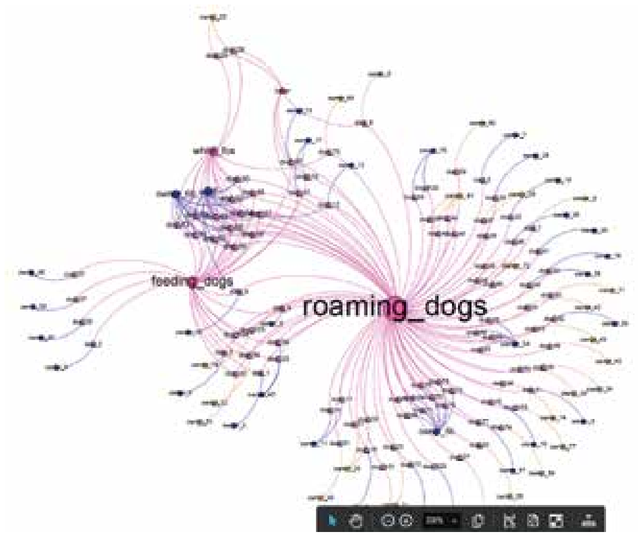

Figure 2. This figure shows how dog-owner pairs are isolated or not and the reported contact between dog and wild mammals, with other dogs because the dog roams free (roaming dogs pool) or because other dog(s) approach(es) the dog when feeds (feeding dogs pool).

Overall, 188 attached dogs were counted. Both attached and free-roaming dogs were observed in residential areas (Figure 3). The number of attached dogs varied from 21 (minimum) to 66 (maximum) in time. A maximum of 16 free-roaming dogs were observed at once with a mean of seven free-roaming dogs observed during each census (Figure 4).

In the cohort study from May-August, 31 dogs were examined, feces were collected from each dog and owners were asked questions about habits (diet composition, housing, medication, exercise, etc.). There was a large proportion of young dogs (less than 2 years-old) (Figure 5). Many dogs had frequent contact with other animals, mostly other dogs (Figure 6).

In the dog cohort in Kuujjuaq (plus environmental samples), we detected *Giardia* in 9 of 36 (25%)

Table 10. Parasite detection in tongues for seals and foxes.

Species (n)	# of positive individuals	Prop Pos (%)
Seal (61)	0	0%
Fox (39)	14	35.9%

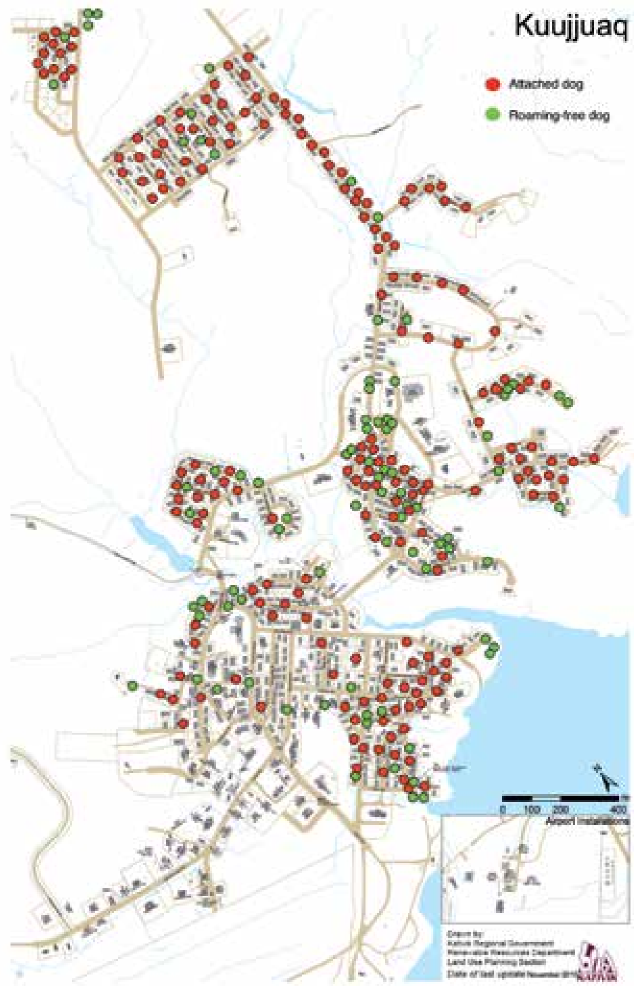

Figure 3. Map of Kuujjuaq showing approximate locations of attached and free-roaming dogs.

and *Cryptosporidium* in 2 of 36 (6%) fecal samples. Further genetic testing will be done to determine if these are zoonotic strains of the parasites. The cohort study will continue in summer 2017 with a reexamination of the same dogs and recruitment of additional dogs, if possible.

c. Findings of the 2016 trail camera study in Kuujjuaq.

Results showed a wide range of wildlife species in and around town: squirrels, wolves, dogs, foxes, rabbits, bears, lynx and different species of birds.

Table 11. Trapped foxes collected in winter 2016-2017.

	Winter 2015-2016	Winter 2016-2017 (to date)	Winter 2016-2017 (target)
NUNAVIK			
Inukjuak	**11**		**40**
Kuujjuarapik	**13**		**40**
Kuujjuaq	**7**		**40**
Puvirnituq	**8**		**40**
LABRADOR			
Happy Valley-Goose Bay	**18**	**11**	**20**
Hopedale			**20**
Labrador City	**12**		**20**
Makkovik			**20**
Nain			**20**
JAMES BAY			
Chissasibi	**10**	**2**	**24**
Wemindji	**7**	**6**	**12**
Waskaganish	**10**	**6**	**12**
Waswanipi	**0**	**0**	**12**
Mistissini	**2**	**0**	**24**
Eastmain	**4**	**5**	
Nemaska	-[a]	**2**	
CÔTE NORD	-[a]	**30**	**50**
Total	**102**	**62**	**394**
[a] **Not sampled**			

Two foxes were observed during this period at cameras located close to the municipal landfill and nearby Lake Stewart. The proportion of fox and dog photos compared to other medium-sized mammals were respectively low (9.6%) and high (83.9%).

Foxes seemed to stay in the periphery of town compared to dogs (to avoid human disturbance), and foxes and dogs seemed to be more frequent in the tundra habitat than in the taiga, with the garbage/dump possibly attracting animals (Figure 7). Contact between foxes and dogs may be infrequent during the summer, with most contacts occurring in the periphery of town (fewer people), and during evening hours (18h-21h) (Figure 8).

Table 12. Interactions of dogs with foxes, bear or wolves were reported rarely.

Animal specie	Proportions (%)
Other dogs	86.6
Raven	52.2
Porcupine	19.4
Red fox	9.0
Bear	6.0
White fox	4.5
Wolf	4.5
Other (rabbits, squirrels, birds, muskox)*	33.8

4) Climate and disease modelling

Arctic rabies modelling

Modelling rabies among red foxes in Southern Ontario

The spatio-temporal distribution of rabies cases in red fox in Southern Ontario is non-random (Figure 9 and Figure 10) and follows a seasonal pattern (Figure 11), which suggests that rabies transmission is driven by seasonal variations in red fox behavior, births and deaths, number and duration of contacts during mating season and co-denning in winter, and immunity to infection (Altizer et al. 2006). Landscape heterogeneity can also cause seasonal changes in the timing, intensity and persistence of rabies epidemics (Altizer et al. 2006). We will use the ORM to determine factors that are most likely responsible for seasonal patterns in case incidence (Figure 11) but also rabies persistence in Southern Ontario (Figure 12).

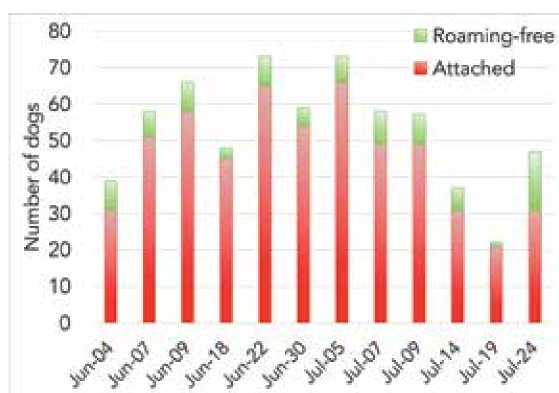

Figure 4. Number of attached and free-roaming dogs seen during each census.

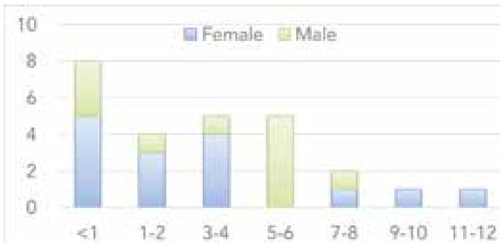

Figure 5. Demographics of dog cohort.

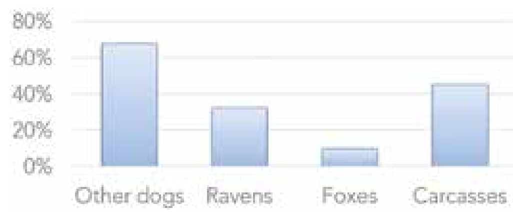

Figure 6. Proportion of dogs having contacts with other animals in the past year.

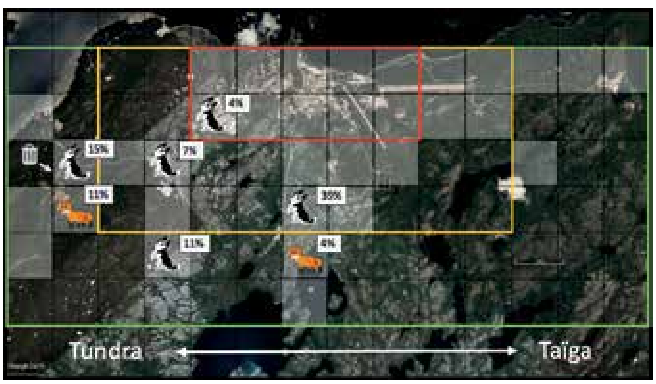

Figure 7. Map of Kuujjuaq representing camera installation, human disturbance zones (red=high, yellow=medium, green=low) and animal observations (foxes and free dogs - number of days with observation). Study period ~ 30 days.

Modelling rabies among Arctic foxes

The analyses of Arctic fox movement revealed variation among individuals in their movement decisions. Arctic foxes exhibited a large range of movement strategies including home-range, nomadic, dispersal, and migration behaviors (Figure 13 and Figure 14). However, the majority (74%) of individuals

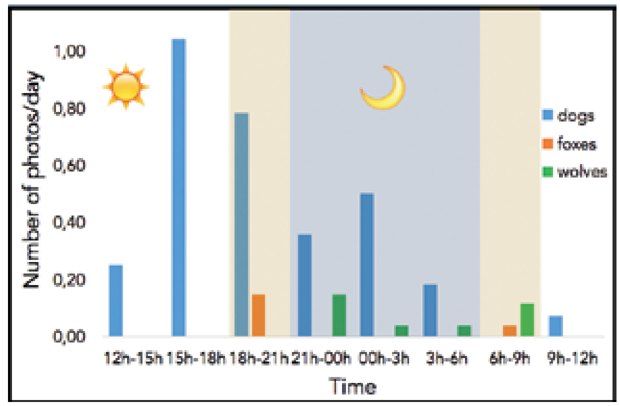

Figure 8. Daily activity of dogs, foxes and wolves.

had home-range (or resident) behavior, consistent with Lai et al. (2016). As we classified Arctic fox movement strategies as resident, nomadic, dispersing, and migrating, these movement modes will be simulated in the landscapes of the ORM and ARM (Figure 15) from a combination of Brownian bridge models (Horne et al. 2007) and bivariate Ornstein-Uhlenbeck processes with attraction points (Breed et al. 2017).

Toxoplasmosis modelling

The Master's thesis is being converted into an article for publication. The model produced a realistic simulation of the ca. 8-year periodicity in cycles of lynx and hare abundance, and this led to simulated inter-annual cycles of infection in lynx, hare and of densities of *T. gondii* oocysts in the environment (Figure 16).

Sensitivity analyses (e.g. Figure 17) identified *T. gondii*-induced mortality in hares, *T. gondii* oocyst mortality in environment, the rate of recovery of lynx, the rate of oocyst excretion by infected lynx, transmission rates from the environment-to-hare and hare-to-lynx, as well as underlying mortality rates of hare as the most influential factors determining the force of infection.

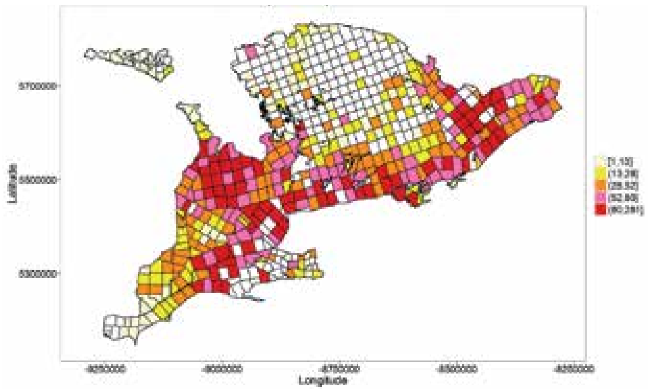

Figure 9. Total number of red fox rabies cases by township from 1957 to 1987 in Southern Ontario. The majority of cases were observed in Southeast and Southwest Ontario.

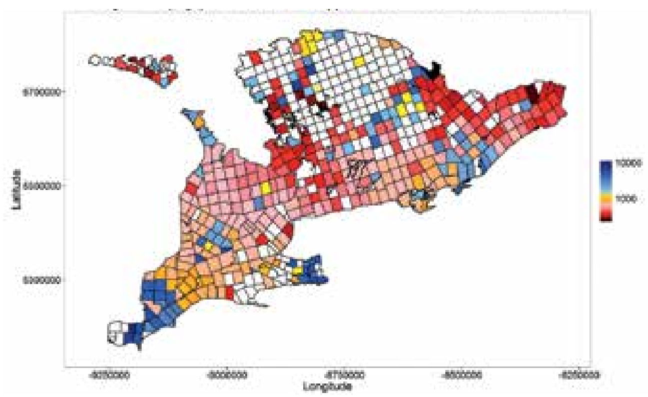

Figure 10. Delay in time (days) relative to the first appearance of red fox rabies in Southern Ontario. Rabies appeared in two entrance points and spread into Southwest Ontario.

DISCUSSION

Food Safety

For the first time in Nunavik, DNA of *T. gondii* was detected in the brain (23%; CI: 13-38%) and heart (39%; CI: 25-54%) of foxes from four communities and in the brain (5.4%; Cl: 0.8-9.9 %) and heart (4.5%; Cl: 0.2-8.8%) of Canada geese from two Hudson Bay communities using state-of-the-art-molecular techniques for the detection of *Toxoplasma* (Opsteegh et al. 2010). However, some tissue positive animals were seronegative, and some tissue negative animals were seropositive.

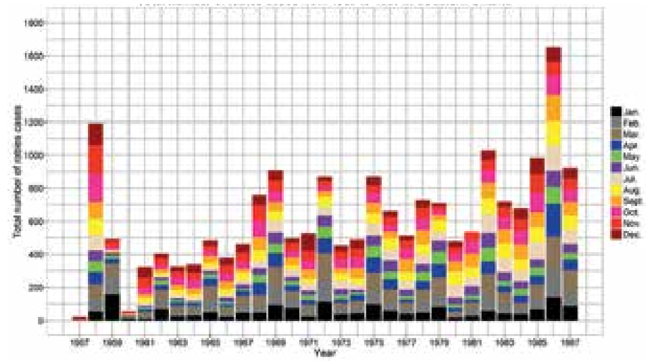

Figure 11. Total number of red fox rabies cases reported by month and year from 1957 to 1987 in Southern Ontario. Peaks of red fox rabies cases were observed during autumn (September – November) and winter (January – March).

These findings have significance for interpreting results of serological studies of wildlife, which have been the mainstay of wildlife research in the past (Jenkins et al. 2013). In comparison to other findings in the North American Arctic, our seroprevalence in fox (39%) was lower than the ~60% found in fox in Central Nunavut (Elmore et al. 2016) and Alaska (Dubey et al. 2011). Our seroprevalence in Canada geese (10%) was higher than 4% reported in a previous study in Nunavik (Leclair and Doidge 2001) and 7% in another population of Canada geese in North America (Verma et al. 2016), and lower than the ~30% reported in snow geese in central Nunavut (Elmore et al. 2014).

Toxoplasma DNA was detected in the breast muscle of two geese, as well as in the liver and gizzard from another individual. Foxes and Canada geese therefore constitute part of *T. gondii*'s ecological niche in Southwestern Nunavik. These results also lend support to the hypothesis that geese may introduce *T. gondii* into the Arctic, where spillover into foxes, and humans, could occur if cysts within geese tissues are ingested. DNA of *Toxoplasma* was not detected in ringed seal, caribou and ptarmigan, although there were seropositive seals and caribou. At the moment, our findings do not change public health messaging about consumption of these wildlife species (seal, caribou, and ptarmigan), which are im-portant for food security and cultural continuity in Nunavik.

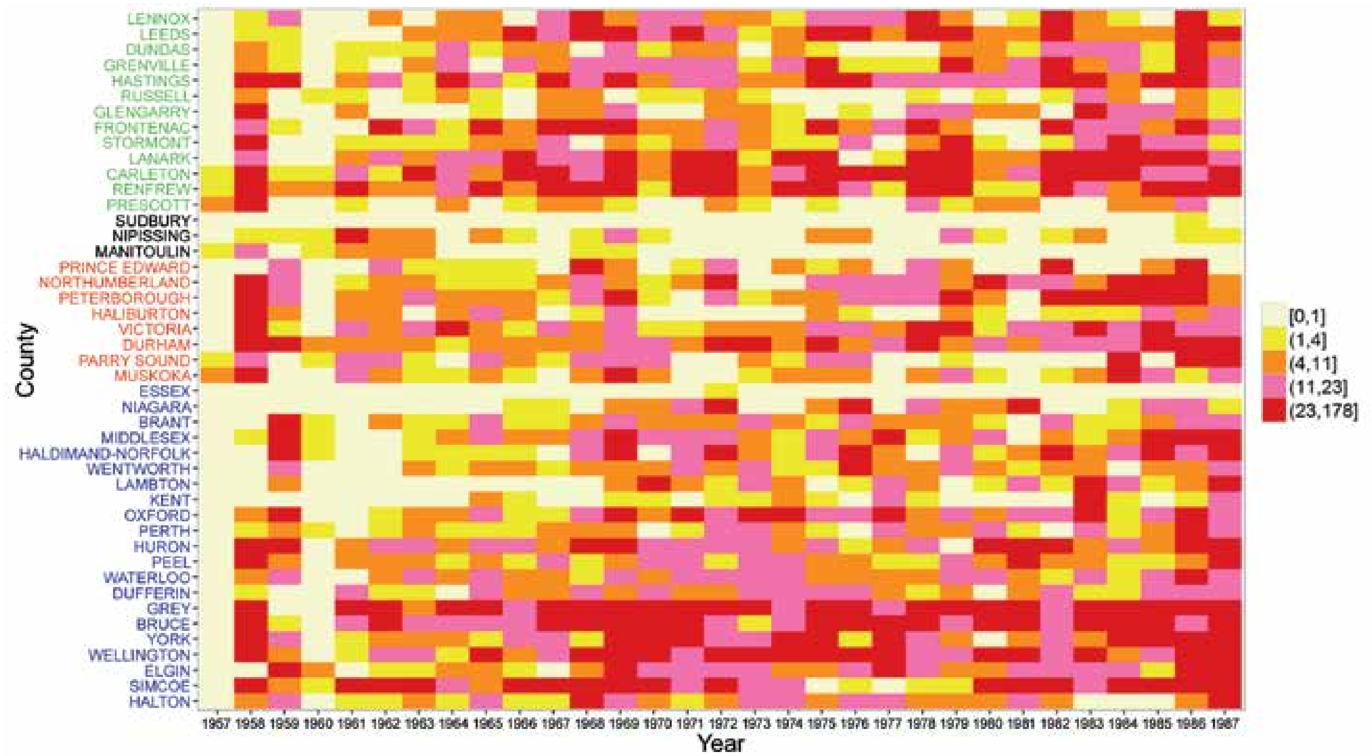

Figure 12. Total number of red fox rabies cases reported by county and year from 1957 to 1987 in Southern Ontario. The counties that are represented in green are located in Southeast Ontario, the counties in black are located in Northeast Ontario, the counties in red are located in Central Ontario, and the counties in blue are located in Southwest Ontario. Rabies persisted in Southeast and Southwest Ontario.

For the first time, *Trichinella* was detected in foxes harvested from four communities in southwestern Nunavik, at much higher rates than previous reports in northern North America (reviewed in Jenkins et al. 2013). This tells us that this parasite circulates in terrestrial ecosystems in Nunavik, and that foxes constitute part of *Trichinella*'s ecological niche. Preliminary genotyping revealed the northern adapted T2 genotype, or *T. nativa* species, which is transmissible to people through consumption of uncooked, unfrozen, and/or fermented meat. Although Inuit do not typically consume fox tissues, it may be important to determine whether *Trichinella* poses an occupational risk for trappers and to determine whether infected prey species for foxes are also consumed by Inuit or their dogs, as part of a One Health approach.

We did not detect *Trichinella* from ringed seals harvested during the time of an outbreak in Nunavik using the larval recovery test recognized internationally as the gold standard (Forbes and Gajadhar 1999). This is consistent with previous findings in northern North America which report prevalences of <1% in seal (reviewed in Jenkins et al. 2013). This was an important and timely outcome of our research, and can reassure people that seal meat remains an important and nutritious country food.

Fox genetics and rabies

Our initial results with 14-locus microsatellite profiles from 90 coloured foxes provided finer-scale resolution of patterns of genetic structure than with nine loci. In particular, the two eastern sampling localities of Cartwright and Port Hope Simpson are genetically

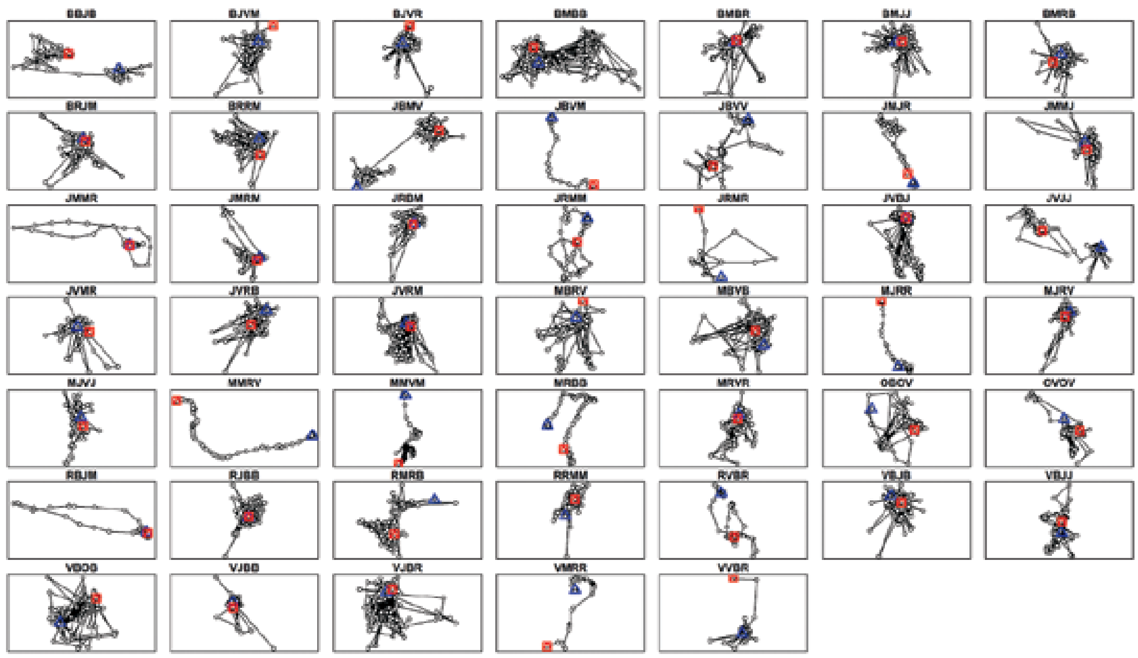

Figure 13. Movement trajectories of 47 Arctic foxes that were tracked with Argos collars from 2009 to 2015, Bylot Island, Nunavut. Canada. The initial and final relocations of each fox are represented in blue and red, respectively.

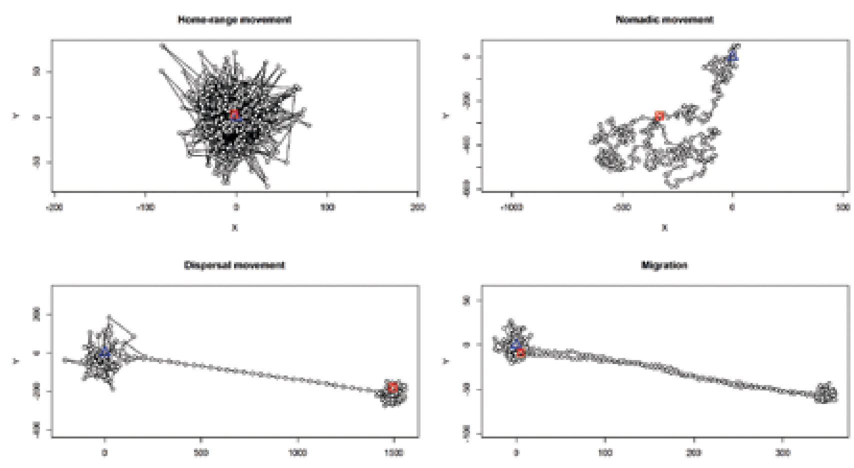

Figure 14. Simulation of the four movement types observed in Arctic foxes: home-range, nomadic, dispersal, and migration behaviors. The initial and final relocations of each fox are represented in blue and red, respectively.

distinct from the central and western Labrador and northern Quebec locations, which group together. The Cartwright sample is the most distinct, possibly due to silver fox-farming activity in the region. Nonetheless detection of limits to gene flow within the region suggests barriers to coloured fox movement at this scale. The additional samples available from different regions in Quebec will allow us to determine the extent of such barriers throughout the Eastern Subarctic. The next steps for this portion of the project are to increase

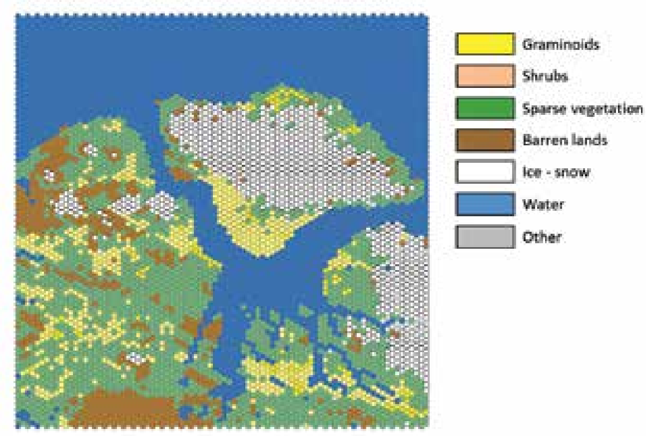

Figure 15. Landscape of hexagonal cells in the Arctic Rabies Model (ARM) representing the study area where Arctic foxes were tracked with Argos collars on Bylot Island, Nunavut, Canada.

the number of loci examined to 20 for all samples and increasing sampling in northern Labrador. Once the data are available for all loci and samples, detailed data analyses to fully document patterns of population structure and gene flow will be conducted.

People, dogs and wildlife

The 2016 census of dogs in Kuujjuaq suggests that there is a variability in the moments that dogs are free-roaming. Moreover, the density of observed dogs is greater in some areas of the community. We detected *Giardia* and *Cryptosporidium* in dog fecal samples, both of which are important causes of human gastrointestinal disease in the Canadian North. Indeed, an outbreak of *Cryptosporidium* in people in Nunavik was caused by a human-associated species (Thivierge et al. 2016), but human cases of diarrhea in Nunavut were caused by zoonotic species of *Giardia* and *Cryptosporidium* potentially shared with animals (Iqbal et al. 2015). Therefore, further genetic characterization of our findings of these two parasites in dogs is very important.

The 2016 trail camera study in Kuujjuaq suggests that contact between foxes and dogs may be infrequent during the summer, and occur primarily near the periphery of town where there are fewer people. Ongoing analyses will test the relationships between the presence/absence of animals in each grid cell and various environmental (food, water, habitat) and anthropogenic factors (dogs, food, human density). This research will continue in 2017, during which foxes captured near the community will be fitted with

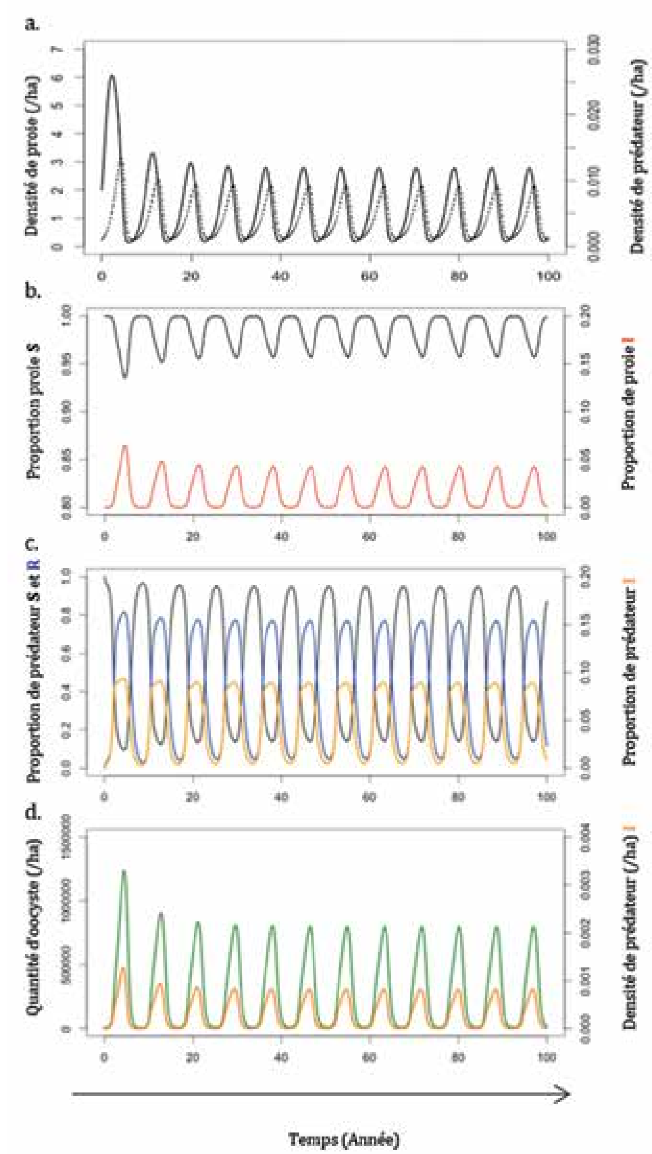

Figure 16. Simulated population dynamics of hare and lynx (panel a), the proportions of hare and lynx infected (panels b and c) and the densities of infected lynx and T. gondii oocysts in the environment (Panel d).

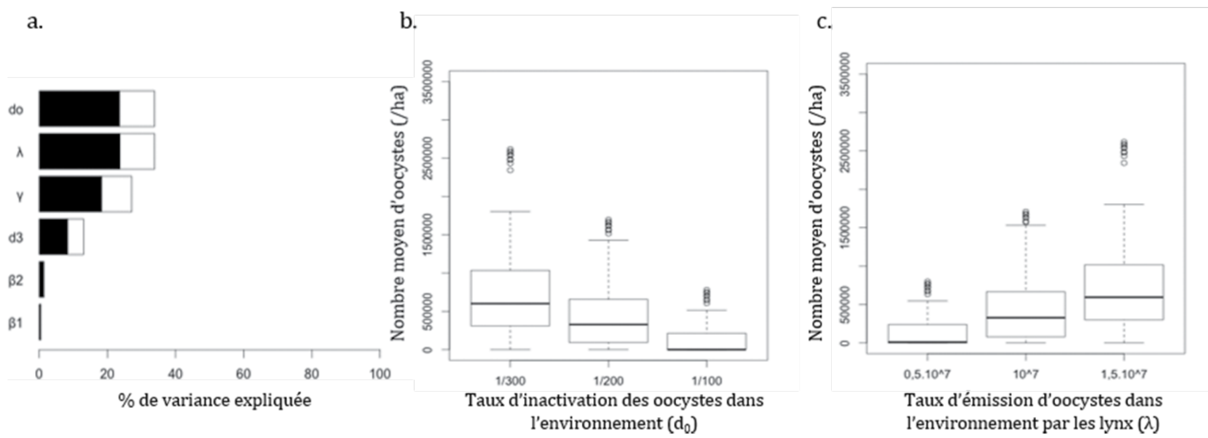

Figure 17. Results of sensitivity analysis for the abundance of T. gondii oocysts in the environment.

GPS collars to track their movements over time and document the contact frequency with people and dogs. In addition, community members will be interviewed regarding their knowledge and observations of foxes and their interactions with wildlife around the village, as well as their perception and knowledge about rabies in their community using a pre-tested questionnaire.

Climate and disease modelling

Our analyses underline the need to incorporate realistic information on movement strategies of individual hosts in the modelling of rabies transmission and spread. The modifications of the movement and epidemiological processes in the Ontario Rabies Model (ORM) and Arctic Rabies Model (ARM) will allow us to determine the ecological mechanisms that induce seasonal variation in rabies outbreaks and how these mechanisms influence spread and persistence of this virus in Southern Ontario as a comparison to the Arctic. Over the coming months, we will perform sensitivity analyses on the ORM and ARM parameters. These analyses will be useful in deciding which are the most important factors driving rabies seasonal dynamics. Ultimately, integrating host movement strategies into the ORM and ARM will provide new insights into the transmission and spread of rabies among red and Arctic foxes and will help to develop more cost-effective prevention programs.

The findings on *Toxoplasma* dynamics suggest that two potentially climate sensitive parameters may affect the abundance of *T. gondii* oocysts in the sub-Arctic environment (and by inference, the quantities of infective oocysts dispersed into the Arctic; Simon et al. 2014). These are mortality rates of snowshoe hare and rates of mortality of oocysts in the environment. This finding provides the information needed for further modelling studies to assess potential impacts of climate change, and for the selection of parameters to investigate in prospective field studies. The next steps in this study are to model effects of climate change on oocyst survival and dispersion, and thus risk to Inuit populations. This work will be initiated through the PhD project of Emilie Bouchard and further funding to support field studies to calibrate and validate such models is being sought.

CONCLUSION

In Year 2, we made progress toward all three of our project objectives. We continued to collect baseline data on prevalence of three priority zoonoses of current animal and public health significance in the Eastern Subarctic, showing that *Toxoplasma* and *Trichinella* are present within the human-wildlife interface in Southwestern Nunavik. We also extended our fox-sampling network in partnership with the Inuit, Cree, and southern trappers to collect more widespread data on fox genetics and rabies, making it possible to document the low prevalence of cyclic rabies in 2015-2016. We advanced current knowledge of the human/wildlife interface for zoonotic disease transmission in the Arctic by collecting data on the frequency and type of wildlife contact with people and domestic dogs in Kuujjuaq and documenting behaviours and cultural practices that affect food-borne zoonotic disease transmission in Inukjuak. Finally, we further developed the Arctic Rabies Model (ARM) simulation platform and identified climate-sensitive parameters affecting persistence of *Toxoplasma* oocysts in the terrestrial environment, preparing these new modelling tools for application to predict future disease risk for people and wildlife within a changing climate, and to evaluate options for risk management. These Year 2 activities position us well to attain our project objectives in year 3 and mobilize this newly generated knowledge through ongoing exchange with our northern partners.

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ECOSYSTEM APPROACHES TO NORTHERN HEALTH

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ABSTRACT

There is an urgent need for innovative interventions fostering Inuit peoples' health. Country foods do not always appeal to Inuit youth and their increasing consumption of highly-processed store-bought foods puts them at elevated risk of obesity and diabetes. This country food diet is believed to be one of the main factors protecting Inuit from many chronic diseases. Country foods provide a unique opportunity to bring together multiple stakeholders with distinct ways of knowing to collaboratively develop and implement community-based interventions targeting multiple objectives: promote Inuit culture, provide outdoor and hands-on learning activities, improve food security, generate opportunities for the social economy, and minimize risks stemming from environmental contaminants and the emergence of chronic diseases.

In 2013, our team engaged the Nunavik regional government, health and school boards, and non-profit partners to develop the "Purple Tongue Project". We developed novel wild berry products (baby puree, roll ups, dried berries, sorbet, etc.) to be produced by Individual Path Learning (IPL) students. The project was piloted in three schools. Between Sept. and Nov. 2013, IPL students harvested more than 40 kg of berries. Roll-ups made by IPL were shared in school and at times sold at the coop. With this intervention, we aim to mobilize Inuit knowledge (IK) and scientific support for wild berries, to improve their consumption and availability throughout the year, give them opportunities to learn IK and engage discussions with elders, propose attractive and local healthy options to sweet beverages and snacks, and stimulate youth empowerment and employment.

Combining cutting-edge science, IK and creative community-driven partnerships is essential for social innovation. The present project aims at mobilizing different ways of knowing about country foods to foster health, well-being, technology translation and empowerment among Nunavimmiut youth. The Axis 1 of the project aims to continue implementing the Purple Tongue project in six Nunavik schools. The Axis 2 aims at developing a new intervention about Nunavik edible mushrooms, an abundant but unexplored local resource. The Axis 3 aims at studying how we can work together to produce and share different from of knowledge to improve our approaches throughout the project. Investing in community-initiatives to build capacity and empower the youth are part of the keys to sustain healthy and resilient Inuit communities and to foster social innovation.

KEY MESSAGES

Biomonitoring of environmental contaminants

- In 2015, Hg and Pb as well as older POPs blood levels were low among participants aged 3 to 19 years old from four First Nation communities in Quebec.
- Although older perfluorinated compounds were low (PFOS and PFOA), one more recent perfluorinated compound (PNFA) was found to be elevated in one of the four First Nation community in 2015, and particularly among children aged 6 to 11 years old.
- Iron deficiency and anemia were highly prevalent (21% and 18% respectively) among First Nation youth in 2015, primarily among girls aged 12 to 19 years old (43% and 26% respectively). Lower iron status was also associated to higher blood manganese.
- Overweight and obesity were very elevated (84%) among youth from two First Nations communities of the Lower North Shore region.
- Up to 23% of Nunavik pregnant women recruited in 2016-2017 presented blood Hg above the Health Canada guideline and sequential hair Hg analyses showed important monthly variations in Hg exposure.
- A few Nunavik pregnant women recruited in 2016-2017 still had blood Pb above the most recent level of concern.

- Up to 60% of Nunavik pregnant women recruited presented iron deficiency and 39% presented anemia.
- Selenoneine represents more than 50% of selenium in beluga mattaaq samples from Nunavik and Nunavut, and smaller amounts of selenoneine have been found in various other species from the Arctic marine food chain.
- Migratory birds of importance to Nunavimmiut may become contaminated during the accidental ingestion of Pb pellets instead of gravel gizzard during their migration outside Nunavik, possibly primarily in James Bay, Newfoundland, Greenland and ranges in the United States. Moreover, these birds may also get contaminated by Pb within the Nunavik territory if the use of Pb pellets persists.

Human health effects of contaminants and contaminant/nutrient interactions

- Major food-chain contaminants and nutrients modify plasma metabolite profiles of Nunavik Inuit adults.
- Selenoneine was identified as a primary Se compound in red blood cells of Nunavimmiut children and adults.
- High Se status during pregnancy prevent Hg-related neurodevelopmental outcomes later at school age.

MISSION AND OBJECTIVES

The Nasivvik Research Chair's mission

- Develop interdisciplinary research and intervention projects in close partnership with Indigenous peoples with a view to conducting innovative research, understanding the complex effects of environmental change on health, working toward prevention, and promoting northern ecosystems as a land to sustain health and wellbeing.
- Support the work carried out at the Axe Santé des populations et pratiques optimales en santé of the Centre de recherche du CHU de Québec to accelerate the training of highly qualified personnel, the recruiting of new researchers, and knowledge mobilization. The chair will also help increase the number of students and researchers active in the fields of environmental and Indigenous health. Particular attention is given to the participation and training of indigenous youth in research since the Nasivvik Chair aims to perpetuate the Nasivvik Centre's mission of "Moving from health research on Inuit, to research with Inuit, and ultimately to research by Inuit".

Over the reporting period, we continued to pursue the objectives of the Research Chair that are the following:

1. Contribute to biomonitoring of environmental contaminants in northern populations and local foods;
2. Study the effects of contaminants on human health and the effects of contaminant/nutrient interactions in foods and on health;
3. Study the prevalence and incidence of zoonoses and other infectious agents, and their environmental and social determinants;
4. Study the effects of local and regional development on the chemical and microbiological quality of drinking water and local foods, and their impact on the health of northern populations and workers;
5. Study the impact of climate and ecosystem changes on local food systems (quality, availability, access, use, sustainability) and on northern health; and
6. Mobilize knowledge into action by:
    a. Integrating, sharing, and discussing research outcomes with co-investigators,

decision makers, key actors, and communities in northern regions;

b. Developing, implementing, and evaluating projects, particularly with youth and in close partnership with regional and local partners;

c. Strengthening the research capacity of Indigenous youth and the capacity of practitioners in the fields of health, social services, the environment, and education;

d. Contributing to regional and national risk assessment initiatives and implementing public health policies; and

e. Taking part in national and international councils and expert panels on Indigenous health and environmental contaminants.

KNOWLEDGE MOBILIZATION

- February 2017: Several consultation activities in Kuujjuaq with the Qarjuit Youth Council, the Nunavik Research Centre and the Nunavik Marine Region Wildlife Board for the BriGHT project, and the Nunavik Nutrition and Health Committee (NNHC) for the review of 2017-2018 NCP proposals and discuss the Chair on-going and future activities.
- March 2017: Invited speaker at the *Forum sur les besoins en recherche des Premiers Peuples* in Val d'Or to consult and discuss with First Nations and Inuit partners the Health Axis health research priorities of the *Institut Nordique du Québec (INQ)*.
- April 2017: Invited speaker at the 2017 Arctic Conference – "New Lights on Northern Prevention Efforts" in Montreal. This conference was targeting physicians and public health professional working in the Arctic, and this year, it was primarily attended by health professionals from the Nunavik region.
- April 2017: Sponsor and chair of a graduate student session at the Journée en santé mondiale de la Faculté de Médecine, ULaval untitled *Atelier sur la recherche aux études des cycles supérieurs: La réalité du terrain.*
- April 2017: Presentation of Orpik's Dream documentary together with ArcticNet at ULaval in the presence of Laura Reitveld, the filmmaker, and Julie Ducrocq, chief veterinarian of the Ivakkak race and PhD student of the Nasivvik Chair.
- April 2017: Participation to the 2-days annual meeting of Human Health group of AMAP and presentation at the following scientific conference at the AMAP conference in Virginia, US.
- May 2017 : Plenary talk at the *Conference Conduire des projets de recherche interculturels: enjeux éthiques* in Quebec City untitled *La recherche en santé autochtone: des connaissances à l'action*.
- May 2017: Invited speaker at the INQ special session of the *Association francophone pour le savoir* (ACFAS) to present a Nasivvik chair activities overview.
- May 2017: Invited speaker at a joint meeting of the First Nations of Quebec and Labrador Health and Social Services Commission (FNQLHSSC) and the First Nations and Inuit Health Branch (FNIHB) of Health Canada at provincial level to present JES!-YEH! project findings and discuss future childhood anemia and obesity prevention programs in Becancourt.
- May 2017: Presentation of Qanuippitaa? 2004 (Q2004) and Utsuk – A Story of Fat documentaries together with ArcticNet at ULaval and in the presence of Pierre Ayotte, Suzanne Bruneau and Chris Furgal, which also presented the future Qanuilirpitaa? 2017 (Q2017) Inuit Health Survey. Caroline Moisan, the 2017 winner of the *Bourse Éric Dewailly pour des projets communautaires en contexte autochtone* sponsored by the Nasivvik chair and untitled "Coming back to communities:

considering attitudes toward early pregnancies" was also announced at that time.

- May 2017: Invited speaker at a joint meeting of the First Nation and Food Nutrition and Environment Study (FNFNES) team, Assembly of First Nations (AFN) representatives and FNIHB at federal level to present JES!-YEH! project findings and discuss the future pan-Canadian Food, Environment, Nutrition and Health of First Nations Children and Youth (FENHCY) Study.
- June 2017: Consultation with 13 health directors and chiefs representing eight out of nine Innu communities in Quebec to present the INQ Health Axis and consult them with respect to health research priorities in their communities.
- June 2017: Publication of an Info-MADO bulletin on the NQN project that was sent to all Nunavik health professionals (Ricard and Lemire 2017).
- June 2017: Presentation of the latest NQN project findings, student projects and other Nasivvik chair activities at the NNHC meeting.
- June 2017: Presentation of the Arctic Bloom documentary together with ArcticNet at ULaval, in the presence of Julie Sansoulet and Joannie Ferland from Takuvik.
- Publication of a letter to the editor entitled *Nunavimmiut helping to protect people from contaminants worldwide* in the Nunatsiaq Online and in paper (Dec 2016 and January 2017) and the Air Inuit magazine (July 2017) (see Appendix 1) co-signed by NNHC and Sarah Kalhok Bourque on behalf of the NCP Management Committee.

INTRODUCTION

Persistent organic pollutants (POPs) and mercury (Hg) emitted in the South travel on major air and oceanic currents to the North to further accumulate in northern wildlife, particularly those at the top of the marine or fresh water food chain (AMAP 2011, 2014). These represent key traditional foods for Indigenous Peoples, which may be exposed to higher levels of these chemicals (AMAP 2015; Donaldson et al. 2010). Fortunately, thanks to several international actions and the Stockholm Convention, which banned older POPs production and emission, these are now going down in northern ecosystems and inhabitants (NCP 2013, In Press). This declining trend was observed in the Arctic (AMAP 2015), and also in First Nation adults in Canada (Assembly of First Nations 2013) and southern Canadian population (Canadian Health Measures Survey-CHMS) (Health Canada 2015). Since 1990's, Hg levels in human populations have also declined markedly. In 2013, Hg exposure had declined by 57% among Nunavik Inuit pregnant women, although 38% still presented Hg blood levels above the Health Canada guideline (Adamou et al. In revision by NNHC; Legrand et al. 2010). In First Nations communities in 2010, most adults presented low Hg exposure (Assembly of First Nations 2013). Since there is actually no evidence that Hg concentrations are actually going down in northern wildlife (Braune et al. 2015), this suggests that in most cases, this declining trend in human exposure is mostly due to a decreased consumption of country foods (Adamou et al. In revision by NNHC). The Minamata Convention on Hg emissions will enter into force August 16, 2017 and longitudinal environmental and human biomonitoring will be needed to confirm that Hg will also eventually go down in northern predatory marine mammal and fish species including beluga, seals, lake trout, pike and walleye (Lemire et al. 2015).

Local activities such as oil exploitation, hydro-electric dams, mining as well as open landfills fires and lixiviation in may also contribute to environmental contamination in the North. In addition, several other chemicals such new POPs and contaminants of emerging concern (CECs) (including flame retardants, perfluorinated compounds, etc.) and less persistent chemicals such as bisphenol A and phtalates are nowadays found in northern ecosystems (AMAP In press) and/or in several consumer goods, including possibly highly-transformed market foods (Zota et al. 2016). On top of this, once a specific contaminant becomes regulated, the chemical industry tends to replace it for a new molecule. Whereas some studies have documented environmental concentration of these more recent other contaminants in northern wildlife (AMAP In press), few data is available about Indigenous communities and local workers exposures to these contaminants, particularly for CECs and less persistent chemicals, and their related health-outcomes (AMAP 2015).

Since 1999, lead (Pb) pellets are banned for hunting wildfowl in Canada and in the Quebec's Province (ECCC 2016). However, Pb pellets are still widely used by hunters in indigenous and non-indigenous communities, and this although Pb-free pellets are easily accessible (Pétrin-Desrosiers 2016). Conversely, Pb bullets are not yet regulated and are the most commonly used ammunition for hunting larger game meat. Moreover, Pb-free bullets are about twice the price and almost impossible to buy in remote regions (Pétrin-Desrosiers 2016). If Pb pellets and bullets fragments are not removed properly from the hunted meat, these may contaminate people relying on these local foods for subsistence (Couture et al. 2012; Fachehoun et al. 2015). Moreover, parts of animal hunted with Pb ammunitions and left on the land also contaminate ravens, foxes and other scavenger animals (Legagneux et al. 2014). Although Pb exposure has decreased markedly in the North after a local voluntary ban in indigenous communities in 1999-2000, Pb exposure was still elevated among few Nunavik pregnant women in 2013 (Adamou et al. In preparation). Documenting ammunition use as well as wildlife and human exposure to Pb is key for the future implementation of policies promoting Pb-free ammunition alternatives across the country.

Several human biomonitoring studies focus on children and pregnant women. Children and youth may be more exposed to contaminants since they often play on the ground and eat proportionally more food than adults. Moreover, the fetus and children are also more sensitive to contaminants since most of these can cross the placental and blood-brain barriers and because their organism is developing. Metals like Hg and Pb are well-known to impair brain development (Pirkle et al. 2016) and most recent studies show that there is no safe level for Pb exposure in children (ACCLPP 2012). Several POPs and less persistent chemicals are also associated with endocrine disruption effects (Tang-Peronard et al. 2014), which may contribute to the actual obesity and diabetes epidemics among First Nation communities (Sharp 2009).

Indigenous populations have conserved a very tight bound to their environment and indigenous knowledge highlights the importance of local foods for health and well-being (ITK and ICC 2012). Indeed, traditional foods are of exceptional quality, rich in protein, several essential elements, vitamins and low in food additives such as sugar, salt, trans- and saturated- fats and other food chemicals mentioned above. Several essential elements found in these foods are known to interact with environmental contaminants, and for example, iron (Fe) or selenium (Se) deficient status may lead to an increased toxicity of Hg, Pb and/or manganese (Mn) (Pirkle et al. 2016; Ye et al. 2017). Consequently, the important food transition amongst indigenous communities towards highly-transformed market foods lead to multiple-burden of diseases: overall poorer nutritional status, increased iron deficiency anemia, obesity and cardiometabolic diseases, and higher exposure and sensitivity to environmental contaminants. Conversely, country foods offer unique potential to bring together a range of knowledge aimed at promoting Inuit culture, preventing chronic illness and the effects of contaminants on health in the Arctic.

In this same vein, a novel Se-compound named selenoneine was recently identified in fish from marine ecosystems, and recent evidence points toward an exceptional concentration of selenoneine in Nunavik marine mammal foods and Inuit blood (Achouba et al. 2016; Yamashita and Yamashita 2010; Yamashita et al. 2013). Selenoneine is a potent antioxidant that has been shown to accumulate in red blood cells together with Hg (Yamashita et al. 2013), and may be the key element involved in Se-mitigating effects against Hg toxicity initially documented in 1970s (Ganther et al. 1972). Specific food sources and health effects of selenoneine remained to be documented in Nunavik.

Another issue related environment and local foods is that some local practices may increase the risk of exposure to certain pathogens. Whereas only sporadic trichinellosis cases occurred between 2000 and 2012, two major human outbreaks of trichinellosis happened in 2013 and 2016 in different Inuit villages (Ducrocq et al. In preparation). In 2004, more than half (59.8%) of Nunavik adults tested positive for *Toxoplasma gondii* and its cycle of transmission remain to be do be elucidated (Messier et al. 2009). Considering the evolution of Inuit culinary practices involving local foods, the increasing exchange of local foods between villages, as well as climate changes impacts on wildlife parasites, documenting the evolution of infectious diseases incidence in Nunavik, together with their respective the protective and risk factors, is critical for promoting safe local food consumption and co-developing tools with hunters to prevent pathogens transmission.

Climate and ecosystem-related changes are also putting increasing pressure on northern environments and affecting the health of northern populations in many ways. This includes the changing access, abundance and diversity of wildlife species as well as the nutrient and contaminant concentrations in these animals (Lennert 2016). These species are key pillars of food security and economic subsistence of northern communities (Rosol et al. 2016). Northern populations are growing rapidly, exerting an increasing pressure on local wildlife resources. Understanding the environmental/ecological combined to the economic and societal factors underlying food security and human nutrition is critical to support indigenous organizations in the co-development of evidenced-based (scientific, local, and traditional knowledge) adaptation strategies to promote food security and sustainable marine harvests in the face of global changes.

ACTIVITIES

Objective 1: Biomonitoring of environmental contaminants in northern populations and local foods

Children and youth in four First Nations communities in Quebec

Project JES!-YEH! - Monitoring of environmental pollutants and health determinants in children and young adults (3 – 19 years old) of a Quebec First Nations community: a pilot study. (PI: Lemire, Health Canada, 2014-2017: $612K).

This pilot study aimed at studying children and young adults (3-19 years) exposure to more than 90 environmental contaminants, document nutritional status and health indicators as well as other health determinants in four First Nations communities in Quebec located in the Abitibi-Témiscamingue and the Lower North Shore regions. This study also aimed to inform the national child study. In 2015, a total of 198 children and youth were involved in the project.

Following the return of results to parents and communities in 2016, several meetings related to the results of the project were held with community partners, the First Nations and Quebec and Labrador Health Services Commission (FNQLHSSC), the Regional Public Health Departments and the First Nations and Inuit Health Branch of Health Canada (FNIHB) in Quebec and at federal levels. Considering the severity of some health issues revealed by the project, several partners are actually getting organised for developing an action plan to prevent childhood and youth iron deficiency and anemia, obesity and diabetes in First Nations communities in Quebec.

Descriptive data analyses are underway for this project. The final report will be provided to communities and Health Canada this summer. In December 2016, the Assembly of First Nations (AFN) adopted a resolution to officially support the realization of the pan-Canadian Food, Environment, Nutrition and Health of First Nations Children and Youth (FENHCY) Study. Lemire will co-lead this new study with Laurie Chan at University of Ottawa and Malek Batal at Université de Montreal (Co-leaders of the FNFNES). This multi-year project is envisioned to start in 2017-18.

Chair MSc students in this project: Emad Tahir (Characteristics of anemia and iron status and their associations with blood manganese and lead among children aged from 3 to 19 years old from four First Nations communities in Quebec). Tahir was awarded first prize for his poster presentation at the *Journée de la recherche* organized by the Santé des populations et pratiques optimales en santé (SPPOS) Axis of the CHU de Québec. A new MSc student, Claudelle Dubeau, was also recruited to work on market food consumption, less persistent contaminant exposure and health outcomes. She will start in September 2017.

Pregnant women and adults in Nunavik

Project Nutaratsaliit qanuingisiarningit niqituinnanut (NQN) – Pregnancy wellness with country foods (Exposure to food chain contaminants in Nunavik: evaluating spatial and time trends among pregnant women & implementing effective health communication for healthy pregnancies and children) (co-PI: Lemire, NCP, 2016-2018: $583K).

This three-year project aims at contributing to on-going international biomonitoring efforts on long-range environmental contaminants exposure among pregnant women in Nunavik and at evaluating the comprehension and effectiveness of health and dietary recommendations among pregnant women, caregivers and the general population. The core objective of this three-year project is to promote healthy pregnancies and children using the highest quality evidence possible with a specific focus on the Nunavik region but also with applications at the international and community scales.

Data collection for the biomonitoring part of the project was completed in March 2017 and a total of 97 Nunavik pregnant women were recruited. All blood analyses for Hg, Pb, manganese (Mn), Se, polyunsaturated fatty acids (PUFAs) and iron biomarkers are now completed as well as the sequential hair analyses for Hg. Analyses for POPs and selenoneine will be completed by August 2017. Individual results letters, both in English and Inuktitut, were sent by mail to all participants in June 2017. Additionally, if the participant consented to, results were also sent to the health professional (doctor, midwife or nurse) involved in the women's pregnancy follow-up. Funding for the second year of the project was granted by the Northern Contaminants Program (NCP). As pregnant women recruitment will be included as part of the Q2017 health survey, funds requested are mainly for the second part of the study (communication).

A paper is in preparation by Adamou : Adamou TY, Riva M, Muckle G, Anassour Laouan-Sidi E, Lemire M, Dery S, Ayotte P (in revision by the NNHC), Temporal trend (1992-2013) of blood mercury and plasma polychlorinated biphenyls concentrations among pregnant inuit women from Nunavik. This paper is based on biomonitoring data from different studies carried on from 1992 to 2013 in Nunavik.

Chair MSc students in this project: Mariana de Moraes Pontual (Exposure to mercury through the food chain in Nunavik: geographical and temporal trends among pregnant women).

Project Q2017: Qanuilirpitaa – How are we now? (co-PI: Lemire, NCP funding for long-range contaminants analysis, 2016-2017: $469K).

Q2017 is a large population health survey that will involve the collection, analysis and dissemination of information about several physical and mental health issues as well as social and ecological determinants of health among Nunavik Inuit youth and adults. Specific objective related to the Chair's biomonitoring activities aims at documenting long-range and metal environmental contaminants exposures (and trends since Qanuippitaa 2004 (Q2004)), their respective ecological and social determinants as well as related physical health outcomes.

In preparation for Q2017, questionnaires to better document sources of environmental contaminants exposure (i.e. food consumption, ammunition use, etc.) were developed, tested, translated to Inuktitut and uploaded on an e-platform. Fieldwork for Q2017 will be held in August-September 2017 (n=2000) on-board the *Admunsen* and visit all 14 communities of Nunavik. While Hg, Pb, Se and cadmium (Cd) will be measured for all participants, pooled samples analyses will be used for legacy POPs, new POPs and CECs. If elevated levels for these latter chemicals are found, individual analysis will be conducted. Algorithms for clinical follow-up of participants with elevated blood Hg or Pb levels are actually being updated (see objective 6). Algorithms were also developed to diagnose anemia, iron deficiency (ID) and iron deficiency anemia (IDA) among the participants that will be recruited during the Q2017 survey.

<u>Nunavik country foods and selenoneine</u>

Sources and distribution of selenium and selenoneine within the Arctic ecosystems (co-PI: Lemire, NCP 2016-2017: $253K).

The objectives of this project is to determine the relative importance of the two primary production pools as sources of environmental Se and selenoneine as well as essential fatty acids. Total Se and selenoneine concentrations are measured along with essential fatty acids distributions throughout a pelagic marine food web, from low-trophic level organisms to top predators. The focus is put on some of the most important pelagic species in terms of energy transfer in the Baffin Bay area. Specimens from a second marine food web that includes benthic species is also being analysed to complete this environmental screening.

Chair MSc student in this project: Francis Dufour (Sources and distribution of selenium and selenoneine within the Arctic Ecosystems). Dufour received a *Bourse en écologie marine* from ULaval as well as scholarships from the *Centre d'études nordiques* and the Northern Scientific Training Program.

<u>Nunavik country foods and lead</u>

Can migratory birds become contaminated with lead during their migration outside Nunavik? A literature review to answer concerns in Nunavik.

During consultation, a member of the Nunavik Hunting, Fishing, and Trapping Association and a midwife from one of the communities in Nunavik, expressed a concern about the possibility that migratory birds could become contaminated with Pb during their migration outside of Nunavik. Together with Sylvie Ricard and Dr Mario Brisson from the NRBHSS, Lemire developed a MSc literature review project to document the possible exposure to Pb, along the migratory routes outside of Nunavik, for the migratory birds most frequently consumed by Nunavimmiut. An extensive literature review was recently completed and a report summarizing the findings was produced.

Chair MSc trainee student involved in this internship project: Cécile de Sérigny (Can migratory birds become contaminated with lead during their migration outside Nunavik?A literature review to answer to concerns rose in Nunavik).

Objective 2: Human health effects of contaminants and contaminant/nutrient interactions

Exposure to environmental contaminants and plasma metabolite profiles among the Inuit of Nunavik (co-PI: Lemire, NCP 2016-2017: $253K).

This project examines the impact of contaminants exposure on plasma metabolite profiles of Inuit adult who participated to the Q2004, while considering the possible mitigating effects of nutrients. Targeted (amino acids (AAs) and acylcarnitines (ACs)) and untargeted metabolomic analyses of plasma samples from 643 fasting Q2004 participants were performed using high performance liquid chromatography coupled to quadrupole-time-of-flight mass spectrometry (HPLC/Q-TOF-MS) at the INSPQ laboratory in Quebec City. For untargeted analyses, raw data were pre-processed and normalized using the SRM 1950 quality control sample. Relations between contaminants and plasma metabolite levels were then assessed using multivariate regression analyses adjusted for age, sex, body mass index, Se, n-3 PUFA and total lipids (PCBs model only). Interactions between contaminants and nutrients are being tested.

Chair MSc student in this project: Cynthia Roy (Exposure to environmental contaminants and plasma metabolite profiles among the Inuit of Nunavik (Northern Quebec, Canada)).

Selenoneine project in children: Is high Se intake from marine diet during pregnancy and childhood neurotoxic or mitigating the adverse effects of MeHg exposure on child development? (co-PI: Lemire, 2015-2016: $122K).

This study aimed at re-analysing Nunavik Child Development Study (NCDS) data in order to evaluate Se neurotoxicity and Se effects on MeHg neurotoxicity in children at 5 and 11 years old, and to estimate dietary sources of Se intake among 11 year-old children in Nunavik. Selenoneine analyses were also recently completed in archived blood samples of participants at 11 years old. We are currently finalizing data analysis and two manuscripts are in preparation.

Selenoneine project in adults: Do country food nutrients protect against mercury toxicity and cardiometabolic diseases? Integrating data from cutting-edge science and mobilizing knowledge towards Nunavimmiut health (co-PI: Lemire, NCP 2016-2017: $253K).

This project is examining associations and interactions between MeHg exposure, nutritional status, and cardiometabolic outcomes and risk factors using data from Q2004 and Q2017. The objective of this project are 1) to assess if validated predictive biomarkers of cardiometabolic outcomes and risk factors are modulated by MeHg exposure and by putative protective factors in the traditional diet including selenoneine and 2) to analyze 13-year cohort data (~800 participants, ≥ 31y) and new cross-sectional data (~2000 youth and adult participants ≥ 16y) that will be collected during Q2017.

Selenoneine and selenoproteins and metabolites of early diabetes were analysed in archived Q2004 samples. Statistical data analyses are underway.

Chair postdoctoral fellow in this project: Matthew Little recently joined the chair's team (Country food nutrients, mercury toxicity, and cardiometabolic diseases in Inuit populations in Nunavik). This year, Little received a Postdoctoral scholarship from the Canadian Institutes for Health Research.

Selenoneine in vitro project: Interactions between selenoneine and methylmercury (MeHg) in red blood cells (RBCs).

The aim of these *in vitro* assays is to test if selenoneine has a protective effect against MeHg toxicity and if selenoneine can enhance MeHg demethylation. To test this, red blood cells (RBC) from healthy individuals are being incubated and exposed to different MeHg concentrations in combination with selenoneine or ergothioneine. Thereafter, RBC will be subjected to a series of tests to evaluate their health (morphology, deformability and oxygen delivery) the level of oxidative stress markers and their enzymatic capacity to reduce oxidative stress. Speciation of Hg will be performed as well in order to determine if demethylation occurred.

Chair BSc student involved at the Institut national de santé publique du Québec (INSPQ): Julie Robitaille. This internship is made possible through a collaborative grant from the Conseil franco-québécois de coopération universitaire, partenariats stratégiques en matière d'enseignement et de recherche – Fonds québécois de recherche en nature et technologie.

Objective 3: Zoonoses and other infectious agents

Prevalence, incidence and risk factors associated with exposure to Toxoplasma gondii, Helicobacter pylori, Cryptosporidium sp. and the rabies virus in the Inuit population of Nunavik.

In order to assess the possibility of developing immunity against rabies while manipulating infected animal carcasses, 198 serums from Q2004 participants that reported practicing traditional activities were tested for rabies antibodies. In addition, 40 fish samples from Nunavik were also sent to Health Canada laboratory to be tested for toxoplasmosis. This will help to better characterise the risk of pregnant women exposure while consuming raw fish.

Within the framework of Q2017, a PhD student is also responsible for studying five diseases and their protective/risk factors: three diseases transmitted by animals (toxoplasmosis, trichinellosis and rabies) and two diseases transmitted between humans (cryptosporidiosis and helicobacteriosis).

A manuscript on communities' involvement and local knowledge during the 2013 trichinellosis outbreak in Inukjuak, Nunavik, is in preparation. A systematic review and meta-analysis about the exposure to *Toxoplasma gondii* from raw or uncooked meat also almost finalized.

Chair PhD student in this project: Julie Ducrocq (Prevalence, incidence and risk factors associated with exposure to *Toxoplasma gondii, Helicobacter pylori, Cryptosporidium* sp. and the rabies virus in the Inuit population of Nunavik). This year, Ducrocq was granted a 3-year doctoral scholarship from the *Fonds de recherche du Québec – Santé* (FRQS), a scholarship from the Northern Scientific Training Program (plus the Éric Dewailly additional scholarship) and a 2017 EcoHealthNet Research Exchange grant at University of California, Davis Campus, One Health Institute (Project: Modelling Infectious Diseases Spillover and Spread). She is also one of the laureate of the *Mon projet nordique* contest co-organized by the INQ and the *Fonds de recherche du Québec*. The laureates of this contest are invited to present their projects at the Arctic Circle Assembly held in Reykjavik, Iceland, in October 2017.

Objective 4: Effects of local and regional development on drinking water and local foods

Exposure to environmental contaminants from local sources in the Arctic: exploratory analyses as part of the 2017 Nunavik Inuit Health Survey Qanuilirpitaa? – How are we now? (co-PI: Lemire, Health Canada, 2017-2019, $85K).

Within the framework of Q2017, additional funding was recently granted from Health Canada to include less persistent contaminants analysis in Q2017 design. These contaminants are most likely from local sources: open landfills fires or lixiviate, oil spills, market foods and consumer goods. These analyses are not covered under the Northern Contaminants Program (NCP) and will be realized on pool urine samples first. If elevated levels are found, analysis will be realized for each participant.

Consultations about the chemicals to include in this project were held in February with the Kativik Regional Government (KRG), the NRBHSS, the NRC and the Canadian Health Measures Survey (CHMS) at Health Canada.

Objective 5: Impact of climate and ecosystem changes on local food systems

GreenEdge – Food Security and Human Health Project

This multidisciplinary research project was initiated in 2013 in the Qikiqtaaluk region (with a focus on the community of Qikiqtarjuaq) to investigate the impact of climate change on Arctic marine ecosystems, and the implications of these changes to Inuit food health and well-being. The aim of the human health dimension of the GreenEgde project (commenced in May 2017) is to assess how climate-mediated changes in the abundance and access to key marine species may impact food security and nutrition in Inuit communities.

Consultations with public health partners in Iqaluit and Qikiqtarjuak are ongoing and consultations with the communities members will be held in August 2017.

Chair postdoctoral fellow in this project: Tiff-Annie Kenny recently joined the chair's team (Qikiqtarjuaq Climate Change and Nutrition/Food Security Project).

BriGHT (Bridging Global change, Inuit Health and the Transforming Arctic Ocean)(co-PI: Lemire, Sentinelle Nord, 2017-2020: $933K).

This project will: 1) assess the synergistic effects of light, warming, acidification and nutrient availability on the accumulation of contaminants and the production of health-enhancing molecules in microalgae, 2) model the transfer of these substances from algae to the upper food web, 3) quantify these substances in local marine foods (LMF) and the blood of Inuit with respect to their food consumption profiles, the visual appearance of LMF, and indicators of food security, well-being and physical and mental health, and 4) implement novel genomic approaches to monitor spatial and temporal changes in the presence and abundance of LMF.

Consultations with Northern partners took place in February 2017. A partnership was establish with Fisheries and Ocean Canada (DFO) for beluga and seal sampling and with the Ministère du Développement durable, Environnement et Lutte contre les changements climatiques (MDDELCC), the Nunavik Marine Region Wildlife Board (NMRWB) and the Regional Nunavimmi Umajulivijiit Katujiqatigininga (RNUK), the Nunavik hunters, fishermen and trapping association, for Arctic char sampling.

Junior researcher mentorship: Jean-Sébastien Moore. Moore was recently granted a *Professeur sous octroi* position at the *Département de biologie* at ULaval. Lemire is providing guidance to Moore so that he can develop a strong research network in Nunavik and an innovative intersectoral research program integrating indigenous health and education together with the relevant practitioners at community and regional levels.

Objective 6: Knowledge mobilization

<u>A) Knowledge integration</u>

- NQN project: Preliminary results were presented and discussed with the NNHC in June 2017.
- *JES!-YEH! project*: In April 2017, a meeting was held with representatives from the FNQLHSSC and the FNIHB of Health Canada at federal and provincial levels to discuss project findings and elaborate a strategy for the follow-up of participants and eventual preventive actions at community level. The FNQLHSSC then invited Lemire and the project team at a joint meeting of the FNQLHSSC and the FNIHB of the Quebec Province in May 2017 in Becancourt to present JES!-YEH! project findings and discuss future childhood anemia and obesity prevention programs among First Nations in Quebec. Discussions are now on-going to organise community meetings to support them in developing their local action plan during the fall. At the end of May 2017, Lemire was also invited to present the project findings at a joint meeting of the FNFNES team, AFN representatives and FNIHB at federal level. Results from the FNFNES study were also presented. The whole team spent the day integrating findings and brainstorming about the scientific rationale, content and design of the future pan-Canadian FENHCY Study. A first draft of the protocol was completed by the research team at the end of June 2017 (PIs Lemire, Chan, Batal, Riva and Zhu). The full protocol will be sent to Health Canada in October 2017. The actual plan is that in 2018-2019, the funding package of the project will be structured for a minimum of eight years (one year by province). During that time, regional consultations will be conducted to refine study objectives and design

research tools and community mobilisation activities. The study recruitment is aimed to start in April 2019.

- *Health Axis – INQ*: The *Forum sur les besoins en recherche des Premiers Peuples* of the INQ was held in Val d'Or in March 2017. Lemire and Riva, co-leaders of the Axis, presented the Health Axis and examples of research activities on-going at ULaval and McGill. First Nations and Inuit partners that were present provided suggestions and comments about the health research priorities for their communities and nations, which were further integrated in the Health Axis conceptual framework. Since representative of the Innu communities had not been fully involved in previous consultation activities, Lemire and Serge Ashini-Goupil (representative for the Innu Nation at the INQ) organised a consultation in June 2017 with 13 health directors and chiefs representing 8 out of 9 Innu communities in Quebec during the First Nation Governance meeting in Trois-Rivières.

B) Capacity building

- Lemire presented the NQN project at the 2017 Arctic Conference – New Lights on Northern Prevention Efforts that was held on April 1-2, 2017 in Montreal. This conference brought together health professionals working in the Arctic, and this year, primarily attended by health professionals from the Nunavik region. Following this presentation, several physicians showed a great interest to be better informed of NQN project findings and better integrate environmental contaminant issues in their clinical practice.
- Three documentaries were presented at the Université Laval in collaboration with ArcticNet: Okpik's Dream (April 20, 2017), Qanuippitaa? 2004 and UTSUK: A Story of Fat (May 18, 2017) and Arctic Bloom (June 15, 2017). About 50 persons were present at each session.
- The second *Éric Dewailly pour des projets communautaires en santé autochtone* scholarship was granted to Caroline Moisan in May 2017 for her project entitled: *Coming back to communities: considering attitudes toward early pregnancy*.
- Lemire contributed to the redaction of an Info-MADO bulletin entitled: *The health professional's role in the current research project in Nunavik: Nutaratsaliit qanuingisiarningit niqituinnanut – Pregnancy wellness with traditional foods* that was published in June 2017 (Ricard and Lemire 2017). This bilingual document was sent by email and mail to health professionals across Nunavik.
- Lemire was invited to give a plenary talk at the *Conference Conduire des projets de recherche interculturels: enjeux éthiques* in Quebec City in May 2017. This conference untitled La recherche en santé autochtone: des connaissances à l'action. Since the president of the CHU de Québec and ULaval Ethical Boards, Me Deleury, showed a great interest for supporting best research practices with indigenous groups, Lemire organised next August a meeting between the *Groupe des Premiers Peuples* of the INQ and Me Deleury, so that the INQ, the CHU de Québec and ULaval will become leaders in indigenous research and using the highest ethical standards.
- Lemire and her team published a letter to the editor untitled *Nunavimmiut helping to protect people from contaminants worldwide* in the Nunatsiaq Online and in paper (Dec 2016 and January 2017) and the Air Inuit magazine (July 2017) (see Appendix 1) co-signed by NNHC and Sarah Kalhok Bourque on behalf of the NCP Management Committee.
- A guidebook on Nunavik wildlife parasites and zoonotic diseases will be developed by Ducrocq (PFSN scholarship) in collaboration with the NRBHSS and the NRC. In winter of 2018, she plans to visit Kuujjuaq, Inukjuak and Puvirnituq (Nunavik) during the Ivakkak race and work with community members and organizations (e.g. RNUK, Unaaq, Saturviit) to consult and build a

collaborative guidebook to prevent wildlife and zoonotic diseases in this region.

- A screening food questionnaire for Hg exposure in Nunavik is currently being developed by de Moraes Pontual. This tool will be used by Nunavik clinicians to identify pregnant women at risk of elevated Hg exposure for further blood Hg testing and nutritional counselling.
- Generally, clinicians and public health practitioners working in Nunavik do not have free access to recent research papers that could be relevant to their field. To address this issue, Vincent Paquin, a MD student doing a summer research internship in the Chair's team, initiated a literature review to build a "Top 10" of most recent scientific papers about Inuit health. This collaborative project is realised in collaboration with Glenda Sandy (Naskapi nurse and MSc student in community health), Dr. Ouellet and Dr. Cauchon (Dept Family medicine), Dr. Gabriel Fortin (MD in Nunavik) and Christopher Fletcher. With the aim of improving knowledge translation, this project consists in selecting and summarizing a top 10 list of recent scientific papers about Inuit health that could influence the practice of clinicians and public health practitioners in Nunavik to: (i) To increase knowledge translation among clinicians and public health practitioners regarding the most recent researches in Inuit health; (ii) As part of the critical appraisal of scientific papers, to develop criteria that recognize and promote the active participation of communities and the integration of cultural aspects of health in research projects conducted in an Indigenous context; and (iii) To initiate students, especially Indigenous students, to research and critical appraisal in the fields of Indigenous and northern health. The literature review is on-going and this fall, Paquin will organise a 2-day workshop with indigenous students from the MD program from the four Medicine Faculties in Quebec for this latest objective. The new CIHR Quebec mentoring network will likewise be involved in this knowledge mobilisation and mentorship activity. Paquin is also in discussion with the Kativik School Board in selected invite high school and cegep Inuit students to participate to the workshop and get to meet indigenous students leaders in the health sector. Paquin aims to have his Top 10 completed and reviewed by the NNHC in February 2018 and disseminated to Nunavik health professionals in March 2018.

C) Risk assessment initiatives and public health policies

- Over the past months, Lemire worked closely with Sylvie Ricard and Mario Brisson from the NRBHSS and Benoit Lévesque at INSPQ, to update clinical algorithms for the follow-up of persons with elevated Hg (Lemire et al. 2016, version 2) and Pb (Lévesque et al. 2002, version 1) in Nunavik in preparation for Q2017 field research. This document will reflect the most up-to-date clinical algorithms on these two contaminants in the country and adapted for the indigenous context, and will be used as background document for other projects like the FENHCY.
- Elevated exposure to Hg and Pb is a public health priority in Nunavik (Bouchard, Congrès Nordique 2017). Based on the NQN project findings, the NRBHSS is actually evaluating the possibility of implementing a systematic Hg and Pb blood screening test of pregnant women to identify those with elevated Hg and Pb exposure to initiate clinical action early during pregnancy and to promote health and well-being from pregnancy to early childhood.
- Lemire's presentations of JES!-YEH! project findings to the FNQLHSSC, AFN and the FNIHB of Health Canada at federal and provincial levels raised a great awareness about the anemia, obesity and diabetes issues among First Nation children, and particularly among teenagers, for which few data is actually available. The nutritionists at the FNQLHSSC

and FNIHB are actually building community tools for local action plans. Lemire will present the project findings to all Quebec First Nation health directors at a FNQLHSSC meeting in the fall and hopefully strengthen collaborative preventive actions between community leaders, the FNQLHSSC, Health Canada and the academic researchers.

D) National and international councils and expert panels

- Lemire participated to the 2-day annual meeting of Human Health group of AMAP and presentation at the following scientific conference at the AMAP conference in Virginia, US. The high prevalence of elevated Hg exposure in Nunavik and importance of considering seasonality of Hg exposure when assessing Hg exposure and related-health outcomes was a great concern/challenge discussed with circumpolar experts. The importance of better considering local contaminants (such as in Objective 4) in circumpolar biomonitoring activities and interdisciplinary projects merging health and environmental datasets and modelling (such as in Objective 5) presented by Lemire was also included in the latest AMAP Human Health group call for actions. The next annual Human Health group AMAP meeting is planned for January 2018 in Norway.
- The Nasivvik chair's biomonitoring projects in the North of the 49th parallel are part of the groundwork for assessing the efficacy of the future Minamata Convention on Hg emission and human exposure that enter into force in August 2017. The UNEP international biomonitoring initiative is led by Nil Basu at McGill University, and Lemire will periodically send updates of the different chair on-going projects.

RESULTS

Objective 1: Biomonitoring of environmental contaminants in northern populations and local foods

Children and youth in four First Nation in Quebec: Project JES!-YEH!

Environmental contaminant exposure:

Hg and Pb exposure are low: 2% and 0% of participants are above Health Canada provisional guidelines (8 μg/L and 100 μg/L, respectively) and the Quebec MADO (*maladie à déclaration obligatoire*) levels. One participant has blood Pb levels just above 50 μg/L, the most recent Quebec MADO guideline for children below 11 years old. Whereas Hg blood levels were slightly higher than CHMS levels (Cycle 2), Pb levels were significantly below Canadian levels for the same age group.

Similarly, almost all older and new POPs were not detected and/or lower than CHMS except three contaminants. Plasma PNFA levels, a perfluorinated compound, were high one of the four communities, and particularly higher among children 6 to 11 years old (median 6.5 μg/L, range 0.4 - 29 μg/L). PFOS and PFOA, older molecules that were later replaced by PFNA and those of longer chain, were very low. PNFA levels in this community were considerably higher than in CHMS and among other circumpolar populations exposed to perfluorinated compounds through long-range transport of chemicals (AMAP 2015). Surflon-111 seems to be the initial molecule involved (chemical signature confirmed by the Centre de Toxicologie du Québec (CTQ)) however until now, no local source has been identified. Environmental investigation is on-going in collaboration with community partners. Second, the 2,5 dichlorophenol urinary metabolite was very high among some participants in one community. The initial molecule involved is the paradichlorobenzene (confirmed by CTQ), an air sanitizer found in moth balls and urinary blocs. In this community, moth balls in toilets were later found to be eaten by children by the school janitors, and were readily removed from the entire school. They sublimate and looked like small candies and are known to give a "feeling". A preventive factsheet will be released in the coming months. Finally, bisphenol A levels in urine were slightly more elevated than CHMS (Cycle 2) among study participants aged 12 to 19 years old.

Nutritional and health status:

Iron deficiency (ID) and anemia were highly prevalent (21% and 18% respectively), not different between study regions and primarily found among girls aged 12 to 19 years old (43% and 26% respectively), which is significantly higher than CHMS for the same age group (13% and 3% respectively) (Figure 1 and 2). According to WHO (2011), anemia prevalence above 20% represents a moderate public health problem. As shown in Figure 2, this was the case for 6-11 years old boys (21%) and 12-19 years old girls (26%) in this study.

Iron is a divalent metal that may interact with manganese (Mn)(Ye et al. 2017). Mn share common absorptive pathways and ID is known cause up-regulation of Mn, thereby increasing Mn intestinal absorption, concentration inside the body, and eventually, its toxicity. In the present study, blood manganese levels were found to be elevated in 12% of participants, which presented blood levels above the former Quebec MADO level (median 15 µg/L, range 7 – 32 µg/L). Like for ID, no difference in blood Mn was found between the two study regions. As shown in Figure 3, serum ferritin, an indicator of iron status, and blood manganese were strongly negatively correlated, supporting the hypothesis that the more iron deficient the organism is, the higher blood Mn levels are. Conversely, hair Mn levels were low and no environmental sources of manganese were found.

According to the International Obesity Task Force criteria for Body Mass Index (BMI) (Cole and Lobstein 2012), overweight and obesity were very high among participants from the Lower North Shore region (18% and 66% respectively). In this region, obesity is primarily found among boys (69%) and participants aged 12 to 19 years old (70%), which is considerably higher than in CHMS Cycle 1 (9.5% for boys and 8.9% for 12-17 years old). A high prevalence of elevated waist-to-height ratio, an indicator central obesity and a stronger indicator of cardiometabolic risk, was also found to be very high in the two regions: 99% and 66% presented abdominal obesity in the Lower North Shore and the Abitibi regions respectively. Moreover, four participants (2%) in the Lower North Shore region were found with elevated glycated haemoglobin and random glucose levels associated to diabetes, of which two were newly identified Type 2 potential cases. One participant in Abitibi was considered pre-diabetic. In CHMS, Type 2 diabetes prevalence for this age groups was 0.3%.

Health determinants:

One-third (34%) of participants from the Abitibi region reported to live in overcrowded dwellings (more than one person per room), which is higher than other First Nations communities in Canada (26%), and non-indigenous population living in Canadian cities (3%). Moreover, up to 42% of participants from the Abitibi region lived in households suffering from food insecurity (6% severe food insecurity), compared to 10% in non-First Nations Canadian households with children.

<u>Pregnant women and adults in Nunavik: Project NQN</u>

Blood Hg, Pb, and Se levels and time-trends:

During Year 1 of the NQN project, a total of 97 pregnant women from 13 communities of Nunavik were recruited for biomonitoring activities. Results show that in 2016-2017, up to 23% of participants still presented blood Hg equal or above the Health Canada provisional blood guidance value of 8 µg/L (Legrand et al. 2010), and 10% had blood Hg equal or above the Quebec MADO guideline (12 µg/L or 60 nmol/L). Table 1 presents time trends for the percentage of pregnant women and women childbearing age (18 to 39 years old) above guidelines for Hg, Pb and Se in Nunavik since 1992. These time trends involve several studies. For pregnant women, these include *NIH 96-2001, Trend 2007, MTP 2011-2012, NCP 2013 and NQN 2016-2017*, whereas for women of childbearing age, these include *Enquête Santé Québec 1992 and Qanuippitaa – How are we?* 2004. As shown in Tables 2 and 3, few participants are still found with very elevated blood Hg levels above 20 µg/L and up to 40.1 µg/L. For this latter participant, Hg speciation analysis showed that it was 95% methylmercury.

Surprisingly, contrarily to blood Hg profile among women of childbearing age in 2004, which showed significantly higher blood Hg among the Hudson Strait region (Lemire et al. 2015), this year, participants from the Hudson Bay region tended to present higher blood Hg compared to other two regions, although the difference was not statistically significant (Geometric mean [range]: Hudson Bay: 4.91 µg/L [0.80 – 40.1 µg/L]; Hudson Strait: 4.02 µg/L [1.00 – 26.1 µg/L]; and Ungava Bay: 3.77 µg/L [1.00 – 16.0 µg/L]). These results suggest that other local important sources of Hg than beluga meat have been consumed during the sampling months (primarily between January and March).

Most recent data analyses by Adamou et al. (in revision by NNHC) on blood Hg time trends between 1992 and 2013 show a significant decreasing trend in Hg exposure since 1992, and that this trend is primarily associated to a decrease trend in marine food consumption. Between 2004 and 2017, a mild but constant decreasing trend in blood Hg seems to be observed. However, as detailed in the next section, these time trends need to be interpreted with caution since considerable monthly variations in Hg exposure are also found.

Se status in Nunavik is known to be among the highest in the world, primarily due to the consumption of marine foods that are exceptionally high in Se such as beluga mattaaq, walrus meat, marine mammal organs and fish eggs (Lemire et al. 2015). As expected, no participant was found to present deficient blood Se levels (below 80 µg/L). A significant declining trend of Nunavik women with Se levels above the Canadian average concentrations (200 µg/L) was found (CHMS 2010, 2013), possibly reflecting the declining trend in marine food consumption as presented above. Still, more than half (55%) of participants had blood Se above the Canadian average and no time trend was observed for participants with exceptional Se status (above 500 and 1000 µg/L), suggesting that marine foods rich in Se were lately consumed by some participants. Like for Hg, the seasonality of country food may lead to significant monthly variation in Se status, although this needs to be confirmed. Selenoneine, a potent antioxidant accumulating in red blood cells and possibly acting against Hg, was found to the major form of Se in Inuit adult blood (Lemire and Ayotte, in preparation), and results for the present participants are expected shortly. As shown in Table 3 below, not surprisingly, blood Se and Hg were strongly correlated and both well associated with Hb, since both selenoneine and Hg are known to accumulate in red blood cells (M Yamashita et al. 2013).

With respect to Pb exposure, no participant presented blood values above the Health Canada and Quebec MADO guidelines of 10 µg/dL. However, few participants (5%; n=5/97) still presented above 5 µg/dL, the most recent level of concern for Pb exposure among pregnant women and children since no safe level of Pb

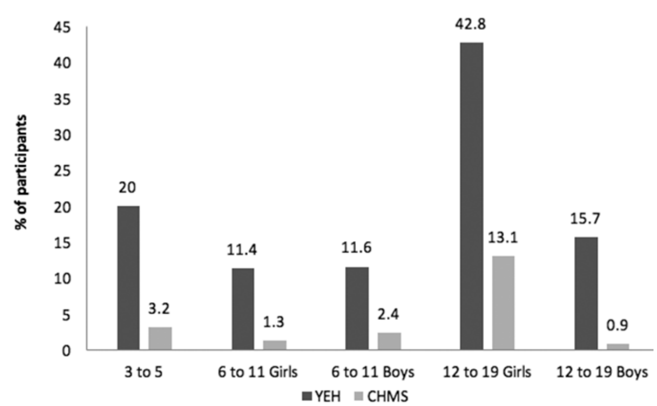

Figure 1. Proportions of ID by age groups in JES!-YEH! vs. other Canadian children from Canadian Heath Measures Survey 2009-2012 (CHMS).

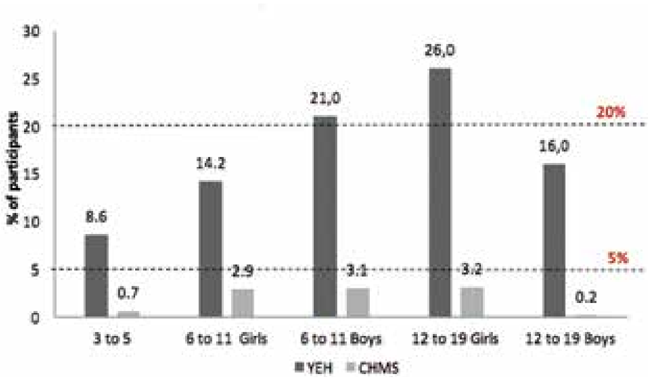

Figure 2. Proportions of anemia by age groups in JES!-YEH! vs. other Canadians. Note: lines refer to WHO reference values for public health significance of anemia, 5%, and 20% referrers to mild and moderate public health problem respectively.

exposure have been found for the foetus and children, and even below 5 μg/dL (CDC 2012). Blood Hg and Pb were also well correlated (Table 3), possibly reflecting the fact that some country foods hunted with Pb-ammunitions also present Hg.

ID, Anemia and IDA prevalence and blood Mn levels:

Up to 60% of the pregnant women recruited presented iron deficiency (ID) (n=58/97). Close to 40% of participants had anemia (39%, n=38/97); 24% (n=23/97) and 15% (n=15/97) had mild and moderate anemia respectively. According to the World Health Organisation, anemia prevalence between 20 and 39% represents a moderate public health problem, whereas a prevalence above 40% highlight a severe public health problem (WHO 2011). Most common type of anemia was iron deficiency anemia (IDA) (30% of total; n=29/97; 76% of anemic participants; n=29/38), whereas nine participants were classified with anemia of unknown origin (UA) (9% of total; n=9/97; 24% of anemic participants; n=9/38).

As for the JES!-YEH! project, few Nunavik pregnant women (9%; n=9/97) were found with Mn levels above the former Quebec MADO guidelines of 20 μg/L, most of which presented ID (78%, n=7/9). As shown in Table 4, blood Mn was significantly negatively correlated with serum ferritin.

Hair Hg concentrations and monthly variations in exposure:

Hair Hg (1st cm) geometric mean and range are 1.86 μg/g [0.32 – 23.2 μg/g] (n=95). As shown in Figure 4, a strong association was found between blood Hg and hair Hg (1st cm) (Person's ρ = 0.95, p<0.0001). The blood-to-hair Hg ratio is known to be about 4:1 (blood Hg in μg/L to hair Hg in μg/g), although there may be important inter-individual variation in the blood-to-hair mercury (Legrand et al. 2010; Liberda et al. 2014). However, in the present study population, the average blood-to-hair ratio was 2.3 [1.1 – 7.7], suggesting an excretion rate twice as high as in other populations, although this remains to be confirmed.

Important monthly variations in Hg exposure (by cm) were found for most participants, from 0.1 to 23.1 μg/g. Moreover, as shown in Figure 2a and 2b, preliminary results suggest that when looking at retrospective monthly hair Hg concentrations (by cm) of participants from the same communities, some similar monthly patterns in Hg exposure emerged. As in Figure 5a, Hg exposure would be greatly higher between June and October in this community. Conversely, in another community, two possible peaks in Hg exposure could be found: one in May-June and one November-January (Figure 5b). However, in other communities, despite important intra-participant monthly variations, no clear common trend between participants was found.
In summary, monthly profiles seems to be more comparable among participant from some specific communities, possibly were local country food access and consumption is more homogeneous between participants. In-depth statistical analysis will be conducted over the coming months.

Awareness of health messages (Part B):

As shown in Table 5 below, whereas most pregnant women (≥ 78%) were well aware of that eating country food is good for health and a good source of healthy fats, only a third (36%) had heard the public message about reducing beluga meat consumption to prevent

Table 1. 1992-2017 time trends between for the percentage of women participants (pregnant women and women of childbearing age) above guidelines for Hg, Pb and Se in Nunavik.

year	N	Age range	Hg ≥ 8 µg/L	Hg ≥ 12 µg/L	Hg ≥ 20 µg/L	Hg ≥ 40 µg/L	Pb ≥ 5 µg/L	Pb ≥ 10 µg/L	Se ≥ 90 µg/L	Se ≥ 200 µg/L	Se ≥ 500 µg/L	Se ≥ 1000 µg/L
1992[WCBA]	164	28 [18-39]	125 (76.22)	88 (53.66)	37 (22.56)	7 (4.27)	121 (73.78)	43 (26.22)	§	§	§	§
1996/97[PW]	78	25 [15-41]	56 (71.79)	41 (52.56)	15 (19.23)	1 (1.28)	47 (60.26)	9 (11.54)	78 (100)	73 (93.59)	13 (16.67)	0 (0)
1998/99[PW]	43	25 [15-37]	22 (51.16)	12 (27.91)	3 (6.98)	0 (0)	21 (48.84)	7 (16.28)	43 (100)	39 (90.70)	1 (2.33))	0 (0)
2000/01[PW]	47	26 [17-39]	29 (61.70)	20 (42.55)	10 (21.28)	0 (0)	18 (38.30)	4 (8.51)	47 (100)	42 (89.36)	6 (12.77)	2 (4.26)
2004[WCBA]	278	28 [18-39]	148 (53,24)	98 (35.25)	43 (15.47)	15 (5.14)	44 (15.83)	8 (2.88)	278 (100)	207 (74.46)	35 (12.59)	5 (1.80)
[&]2004[PW]	31	27 [18-42]	16 (51.61)	11 (35.48)	2 (6.45)	0 (0)	2 (6.45)	0 (0)	31 (100)	22 (70.97)	5 (16.13)	0 (0)
2007[PW]	42	24 [18-37]	7 (16.67)	4 (9.52)	1 (2.38)	0 (0)	2 (4.76)	0 (0)	42 (100)	22 (52.38)	2 (4.76)	0 (0)
2011/12[PW]	111	24 [18-39]	40 (36,04)	22 (19.82)	6 (5,41)	1 (0,90)	4 (3.60)	2 (1.80)	111 (100)	84 (75.68)	25 (22.52)	5 (4.50)
2013[PW]	95	24 [18-41]	36 (37,89)	12 (12.63)	3 (3.16)	0 (0)	1 (1.05)	0 (0)	95 (100)	67 (70.53)	18 (18.95)	2 (2.11)
2016/17[PW]	**97**	**25 [16-40]**	**22 (22.68)**	**10 (10.31)**	**2 (2.06)**	**1 (1.03)**	**5 (5.15)**	**0 (0)**	**97 (100)**	**53 (54.64)**	**3 (3.09)**	**1 (1.03)**
P-trend[*]			**<.0001**	**<.0001**	**<.0001**	**0.0531**	**<.0001**	**<.0001**		**<.0001**	**0.9720**	**0.3615**

PW = pregnant women; WCBA = women of childbearing age.
[&] Not included in the trend test; [*] Based on Cochrane-Armitage trend test; § Only 8 subjects with blood Se.

acute Hg exposure and even less (16%) were aware of the importance of avoiding lead shots (pellets) for hunting to prevent Pb exposure.

Pregnant women and adults in Nunavik: *Project Q2017: Qanuilirpitaa – How are we now?*

Fieldwork for Q2017 will be held in August-September 2017 (n=2000) on-board the *Admunsen* and visit all 14 communities of Nunavik. Preliminary results about exposure to metal and long-range contaminants will be available in January 2018.

Nunavik country foods and selenoneine

Selenoneine, an organic form of selenium, represents more than 50% of selenium in beluga mattaaq samples Nunavik, Nunavut and the St. Lawrence River, and selenoneine content found in this specific country food is higher than other foods like bluefin tuna considered to be high in selenoneine (Yamashita et al. 2013). The present project also show that selenoneine is also found in lower parts of the Arctic food chain, and particularly in the benthic food chain (bivalves and walrus), but at in a smaller proportion than in beluga mattaaq.

Nunavik country foods and lead

This literature review identified snow geese, Canadian geese and common eiders as the main species consumed by the Inuit for their flesh and eggs. Pb pellets are still used for hunting in parts of geese migration territories, including James Bay, Newfoundland and various American ranges. For the common eider, their migration also takes them to James Bay and Newfoundland, as well as Greenland where the sale and use of Pb shots have been banned only since 2014. Both geese and eiders can be contaminated with Pb shots embedded in their body when they survive their wounds. These three species can also be contaminated by the accidental ingestion of Pb pellets, which they confuse with gravel (useful for their gizzard), and there is every indication that this is their main pathway of exposure to Pb when birds migrate in regions where Pb pellets are still used. Finally, females of these Pb contaminated species may present Pb in their eggs and feathers at varying concentrations.

Table 2. Blood Hg, Pb and Se geometric mean and range between 1992 and 2017.

year	N	Age range	Hg µg/L	Pb µg/L	Se µg/L
1992^{WCBA}	164	28 [18-39]	12.93 [2.0-72.1]	7.13 [1.45-42.9]	147.8 [115-224]
$1996/97^{PW}$	78	25 [15-41]	11.98 [3.81-44.29]	5.33 [1.04-25.88]	332.7 [186-976]
$1998/99^{PW}$	43	25 [15-37]	7.68 [2.61-31.26]	5.34 [1.86-13.3]	295.6 [150-575]
$2000/01^{PW}$	47	26 [17-39]	9.35 [1.60-38.1]	4.08 [1.04-13.7]	304.6 [187-1228]
2004^{WCBA}	278	28 [18-39]	8.58 [0.20-164]	2.78 [0.66-20.7]	280.8 [126-1339]
$^{\&}2004^{PW}$	31	27 [18-42]	7.64 [1.20-30.1]	1.85 [0.58-8.49]	265 [126-701]
2007^{PW}	42	24 [18-37]	4.05 [0.68-24.1]	1.61 [0.66-7.66]	228.9 [134-709]
2011^{PW}	111	24 [18-39]	4.97 [0.18-40.1]	1.30 [0.27-23.4]	315.4 118-2992]
2013^{PW}	95	24 [18-41]	5.20 [0.28-32.1]	1.41 [0.42-6.21]	303 [126-1417]
$2016/17^{PW}$	**97**	**25 [16-40]**	**4.28 [0.80-40.1]**	**1.20 [0.41-9.25]**	**227.9 [118-2205]**

PW = pregnant women; WCBA = women of childbearing age.

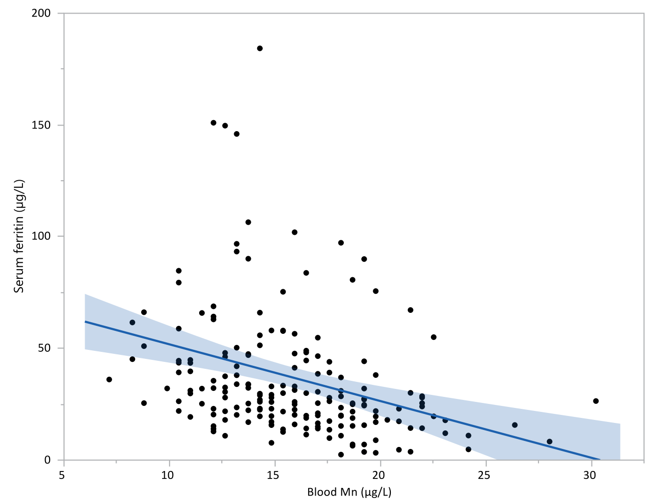

Figure 3. Association between serum ferritin and blood Mn in JES!-YEH! (Spearman ρ = - 0.42, p < 0.0001).

In summary, migratory birds of importance to Nunavimmiut may become contaminated during the accidental ingestion of Pb pellets instead of gravel gizzard during their migration outside Nunavik, possibly primarily in James Bay, Newfoundland, Greenland and ranges in the United States. Moreover, these birds may also get contaminated by Pb within the Nunavik territory if the use of Pb pellets persists. This project will support the communication campaign by the Nunavik Regional Board of Health and Social Services to prevent exposure of Nunavimmiut to Pb to be launched next fall.

Objective 2: Human health effects of contaminants and contaminant/nutrient interactions

Exposure to environmental contaminants and plasma metabolite profiles among the Inuit of Nunavik

Using linear regressions, it was observed that plasma PCBs and blood MeHg levels were positively associated with plasma concentrations of several ACs and AAs (Table 5), whereas some negative associations were observed between blood Se and metabolite concentrations. Statistical analyses for metabolites identified through untargeted metabolomics are also ongoing.

Table 3. Non-parametric correlation matrix (Spearman's ρ correlations) between blood Hg, Pb, Se, Mn, Hb and SF among study participants (n=97).

Hg, Pb, Se, Mn, Hb and SF among study participants (n=97)

	Hg	Pb	Se	Mn	Hb	SF
Hg		**0.33***	**0.67*****	- 0.08	**0.32****	0.19†
Pb			- 0.03	- 0.17†	0.18†	0.10
Se				0.05	**0.38****	0.19†
Mn					- 0.05	**- 0.21***
Hb						**0.34****

*** p<0.0001; ** p<0.01; * p<0.05; † p<0.10

Selenoneine project in children: Is high Se intake from marine diet during pregnancy and childhood neurotoxic or mitigating the adverse effects of MeHg exposure on child development?

Re-analysis of the NCDS data highlights that MeHg exposure is deleterious only among children with low prenatal Se status. This is the first longitudinal study to provide empirical data on the protective effect of Se against almost all negative effects of MeHg that NCDS study evidenced on child development at 11 and 5 years old.

Blood selenoneine analysis in archived NCDS blood samples at 11 years old were added to the study design and results show very similar to Inuit adults: selenoneine is also found in children's blood and selenoneine concentration is well correlated with blood total Se, suggesting that total Se is a surrogate for selenoneine in population living off marine foods and beluga mattaaq consumption.

Two manuscripts are in preparation. Whether selenoneine is also positively associated to neurodevelopmental child development will be examined shortly.

Selenoneine project in adults: Do country food nutrients protect against mercury toxicity and cardiometabolic diseases? Integrating data from cutting-edge science and mobilizing knowledge towards Nunavimmiut health

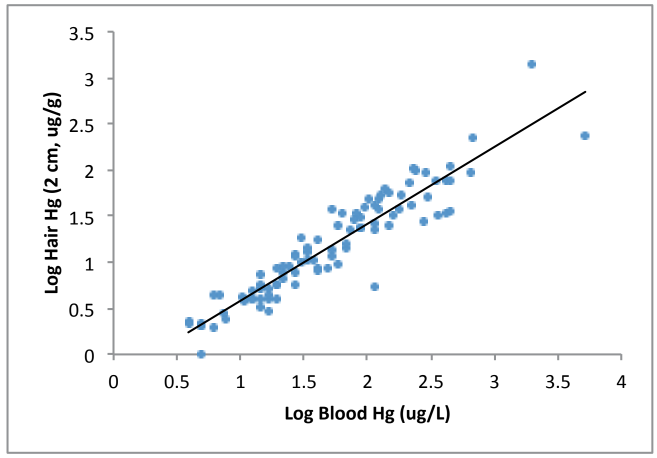

Figure 4. Association between blood Hg and hair Hg (average 2 first cm) (n=94). Both variables were log-transformed.

Selenoneine was identified as a major selenium compound in red blood cells of Nunavimmiut adults, and the percentage of selenoneine is strongly and positively correlated with blood total Se concentrations (Lemire and Ayotte, in preparation). Whether or not selenoneine protects against MeHg cardiotoxicity will be examined shortly.

Selenoneine in vitro project: Interactions between selenoneine and methylmercury in red blood cells (RBCs)

No results are available yet for the new analyses that are currently realized.

Table 4. Percentage of awareness of about health messages among pregnant women that participated in the project (n=97).

Advices or messages*	Yes (%)	No (%)	Don't know (%)
Country foods are a good source of healthy fats	78	19	3
Generally, eating country foods is good for pregnant women	90	8	2
Generally, eating country foods is good for a developing foetus (the baby developing inside the mother)	85	9	6
Pregnant women should reduce the amount of beluga meat they eat	36	57	7
Hunters should avoid the use of lead shot for hunting	16	69	14

*Question: Have you heard any of the following advice or messages?

Table 5. P-values of linear regressions adjusted for age, gender, smoking status, Se level, and omega-3 levels and total lipids (PCBs only) to measure the association between exposures to environmental contaminants and metabolic signature in targeted analysis.

	Mercury	BPCs
Acetylcarnitine	NS	0.0067
Butyrylcarnitine	NS	NS
Carnitine	NS	NS
Glutarylcarnitine	NS	0.0358
Hexanoylcarnitine	NS	0.0006
Isobutyrylcarnitine	0.0405	<0.0001
Propionylcarnitine	NS	0.0017
Octanoylcarnitine	NS	0.0350
Arginine	NS	0.0016
Glutamic acid	NS	0.0011
Isoleucine	NS	NS
Leucine	NS	NS
Methionine	NS	0.0099
Phenylalanine	NS	0.0086
Tyrosine	NS	NS
Valine	NS	0.0417

Objective 3: Zoonoses and other infectious agents

<u>Prevalence, incidence and risk factors associated with exposure to Toxoplasma gondii, Helicobacter pylori, Cryptosporidium sp. and the rabies virus in the Inuit population of Nunavik</u>

Only two of the 198 Q2004 individuals tested for rabies antibodies demonstrated antibody levels superior to 0.5 UI. The medical chart review revealed that one of these individuals received a post-exposition vaccination which would explain the level measured for this individual. We are presently in the process of reviewing the medical chart of the second participant. Results for toxoplasmosis analyses in Nunavik fishes will be available soon. Preliminary results about zoonosis and infectious diseases prevalence will be available in January 2018.

Objective 4: Effects of local and regional development on drinking water and local foods

Fieldwork for Q2017 will be held in August-September 2017 (n=2000) on-board the *Admunsen* and visit all 14 communities of Nunavik. Preliminary results about exposure to less persistent contaminants will be available in April 2018.

Objective 5: Impact of climate and ecosystem changes on local food systems

The GreenEdge – Food Security and Human Health Project and the BriGHT are just starting. Preliminary results will be available in January 2018.

DISCUSSION

Biomonitoring research reveals very different issues between indigenous regions. Among First Nations communities involved in the JES!-YEH! project, Hg and Pb exposure was quite low and not that different from the Canadian population of the same age groups (Lye et al. 2013). One participant was found with borderline elevated Pb levels. While returning results to parents of participants, only few were aware that some ammunition could lead to Pb exposure. This highlights the importance for promoting Pb-free ammunitions across all indigenous regions, particularly for baby guns that are often used by teenagers, to prevent the contamination of local wildlife by lead pellets and bullets, and to promote the consumption of traditional

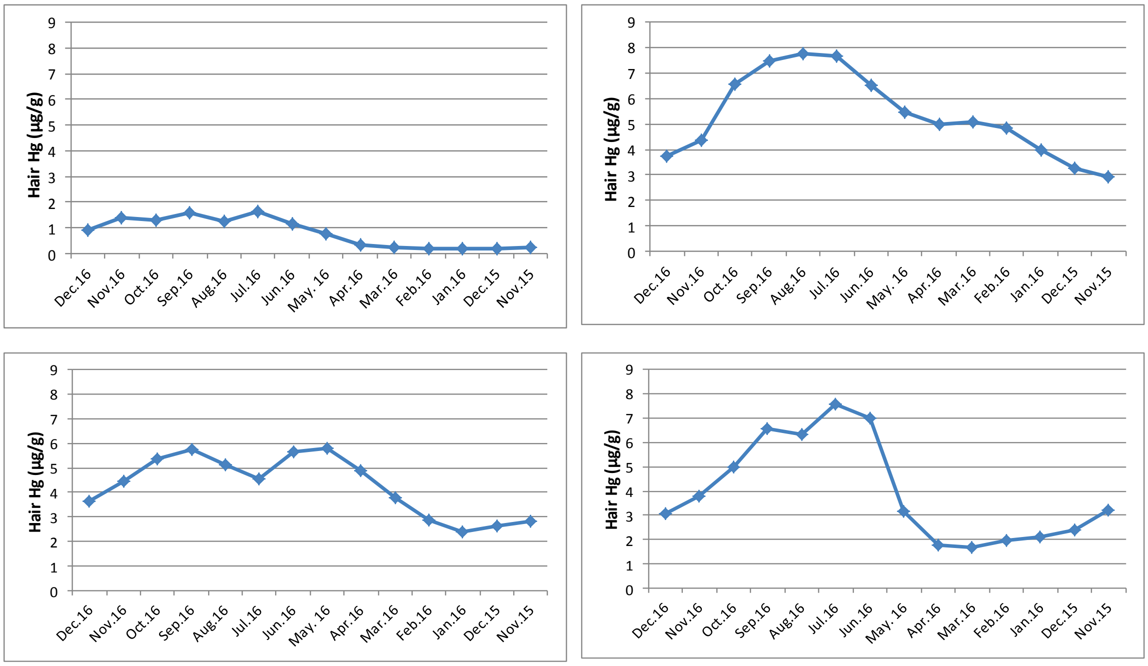

Figure 5a. Example of four participants' hair Hg monthly profile from one community with one peak in Hg exposure between June and October.

foods while avoiding Pb exposure. Considering the elevated prevalence of iron deficiency, anemia, elevated Mn, obesity and diabetes in this study population, strong and rapid multilateral actions are needed to promote active livelihoods, healthy eating as well as traditional foods harvest and consumption and to strengthen positive community leaders to curb down the progression of multiple-burden of diseases among indigenous youth.

Conversely, in Nunavik, Hg exposure is still very elevated (23%) compared the Canadian population, among which the majority (97.8%) of women aged 16 to 49 years, including pregnant women, had blood Hg below 8 µg/L in 2007-2009 (Lye et al. 2013). Considering the important regional and monthly variations in Hg exposure in Nunavik, further analyses are needed to: (i) better characterise regional and monthly variations in Hg exposure and identify local sources of Hg exposure and; (ii) develop a screening questionnaire to be used by health professionals to identify with high sensibility and specificity the pregnant women at risk of elevated Hg exposure. Our preliminary findings highlight that further data analysis for Hg time trends should take into account the month of recruitment and/or the region of origin in order to tentatively better assess time trends in Hg exposure among women in Nunavik.

Moreover, in Nunavik, few participants (5%) were still found with blood Pb above the most recent level of concern. As previously shown by Plante et al. (2011), iron-deficiency anemia is very prevalent among pregnant and Inuit women in Nunavik (39%). Several country foods are known as excellent sources of iron (Government of Nunavut 2013) and, as promoted by NRBHSS, country foods may also better prevent anemia than market foods and supplements. As for the First Nations communities, joins efforts between researchers and several Nunavik partners not only from the health sectors (NRC, KRG, NMRWB, Unaaq, RNUK, etc.) are important to jointly address contaminant exposure and anemia issues in Nunavik.

The project with First Nations youth revealed that although most POPs exposure is low, the elevated levels of PFNA, a new POPs, in one community

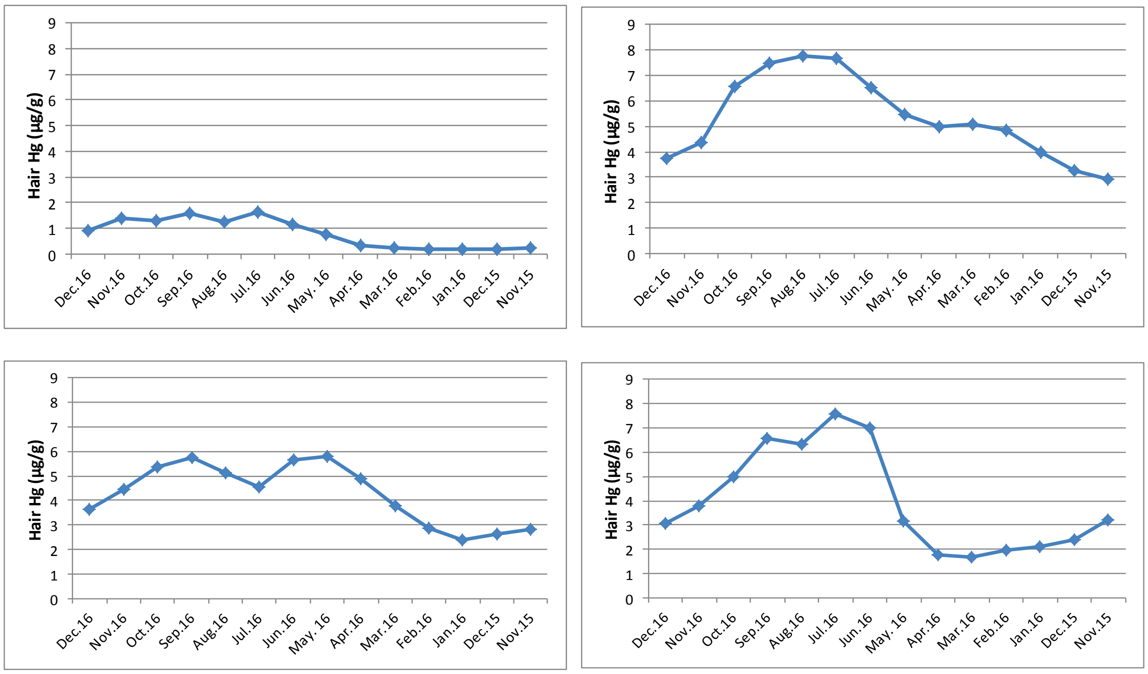

Figure 5b. Example of four participants' hair Hg monthly profile from one community with two peaks in Hg exposure between May-June and November-January.

highlight a possible important source for this chemical now replacing older PFOS and PFOA. Further local investigation is needed to tentatively identify the local source of PFNA exposure among children. Globally, this shows that large screening for new chemicals, and not only for those transported over long distances, is important for better understanding the impact of local development and global changes in indigenous communities.

For the NQN project, more data on selenoneine, legacy and new POPs and CECs are expected shortly. Further analysis to document pregnant women's food security, housing conditions, drinking water source, practice of traditional activities and Pb-ammunition use, health behaviors (cigarette, marijuana and alcohol consumption) and country food consumption, awareness of health messages, and its associations with contaminants exposure (Hg, Pb and others) and nutrient status (iron status, selenoneine, omega-3 fatty acids) will be conducted over the coming months.

The selenoneine projects highlight the importance of marine foods for Inuit health. Our data showing protective effects of prenatal elevated Se status and selenoneine on MeHg developmental toxicity is a first that have not been observed elsewhere. For instance, in the Faroese, only pilot whale meat and blubber are consumed (not the skin), and Se status is much lower than in Nunavik, thus explaining why Se and selenoneine protective effects were never observed in this marine mammal eating population highly exposed to MeHg (Choi et al. 2008). More data about selenoneine interactions at cellular and with respect to cardiometabolic outcomes are expected shortly and will be readily shared with our Inuit partners.

CONCLUSION

Actual research findings highlights the complexity of food and contaminants related issues in the North, since community are currently a multiple-burden of diseases simultaneously (anemia, obesity, cardiometabolic, etc.) and solutions have to be adapted to the specific needs and reality of each community. Moreover, climate changes, biodiversity loss or changes, the increasing demography of indigenous communities exert increasing pressure on local food resources. Conversely, several great leaders are mobilized for positives changes in their communities and Q2017 is emerging an amazing example of this indigenous re-appropriation of local health governance and healing practices[1]. Intersectoral research is fostering research/practitioners teams to develop innovative interventions and use better research practices. Strong efforts will be made to train more indigenous students in the field of health research.

The Nasivvik Chair is unique opportunity to consolidate several research projects on-going in northern environmental and indigenous health at Université Laval, and thmost recent project on global changes and Inuit health are great examples of this. It also creates a great environment for indigenous and non-indigenous student training and for gaining the skills and experience for cutting-egde science and in community-based research. The next year will focus on Junoir 2 FRQS fellow application, data analysis, manuscript publications, community and regional report dissemination and preparation of future FENHCY study. Next months will also be critical to recruit more graduate students and secure funding for the Nasivvik Research Chair after 2018.

ACKNOWLEDGEMENTS

All these projects would never be possible without community members participation in our projects, from 3 years old to elder's age! Their active involvement, suggestions, support, storytelling and invitations to community activities are always a unique moment of exchange and to foster our knowledge of indigenous diverse cultures, health issues and local environment. It's also a great moment to get their inputs for better research. Nakurmikarialuk! Megtweetch! Tshinashkumitin!

We also thank the NNHC, the NRBHSS, the NRC, the KRG, the NMRWB and the FNQLHSSC for their support and advice. Partnership with northern institutions is crucial for meaningful and high-impact science at local, regional, federal and international scales; their guidance and support is of inestimable value.

Funding for these projects was provided by the Northern Contaminants Program (Aboriginal Affairs and Northern Development Canada), Health Canada, Sentinelle Nord and the ArcticNet Network of Centres of Excellence of Canada and Health Canada.

[1]http://www.ledevoir.com/societe/actualites-en-societe/502283/amundsen-recherche

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Appendix 1

LETTRE OUVERTE - GREAT OUTDOORS — ÉTÉ - SUMMER 2017

Thank you Nunavimmiut for your invaluable collaboration!

Over the past 30 years, more than 3,000 Nunavimmiut have participated in studies that revealed high levels of persistent organic pollutants (POPs) and mercury in their blood. This information was used by the Inuit Circumpolar Council, the Government of Canada and other organizations to advocate for a global ban on production and use of POPs, leading to the adoption of the Stockholm Convention in 2004. Nunavimmiut who participated in these studies directly helped to reduce exposure to POPs in the Arctic and worldwide!

Ratified by Canada on April 7, 2017, the Minamata Convention to reduce mercury emissions should enter into force shortly. The collaboration of Inuit is still very much needed to monitor the efficacy of global efforts aimed at reducing mercury in wildlife and protecting the health of Nunavimmiut.

Thanks from all of us and our organizations

Elena Labranche, Chairperson of the NNHC, on behalf of Nunavik Nutrition and Health Committee members.

Mélanie Lemire, Titular of the Nasivvik Research Chair and Assistant Professor at the Université Laval, on behalf of Gina Muckle, Pierre Ayotte, Chris Furgal, Amanda Boyd, Richard Bélanger, Michel Lucas, Catherine Pirkle, professors from the Université Laval, Trent University, Washington State University, and the University of Hawai'i at Manoa.

Sarah Kalhok Bourque, Chair - Northern Contaminants Program, Indigenous and Northern Affairs Canada, on behalf of the Northern Contaminants Program Management Committee.

Merci à vous, Nunavimmiut, pour votre précieuse collaboration !

Au cours des 30 dernières années, plus de 3000 Nunavimmiut ont participé à des études qui ont révélé des niveaux élevés de polluants organiques persistants (POP) et de mercure dans leur sang. Le Conseil circumpolaire inuit, le gouvernement du Canada et d'autres organismes ont utilisé cette information pour plaider en faveur de l'interdiction dans le monde entier de la production et de l'utilisation de POP, jusqu'à l'adoption de la Convention de Stockholm en 2004. Les Nunavimmiut qui ont participé à ces études ont directement contribué à la réduction de l'exposition aux POP, dans l'Arctique bien sûr, mais aussi partout sur la planète !

La Convention de Minamata visant à réduire les émissions de mercure, ratifiée par le Canada le 7 avril 2017, devrait entrer en vigueur sous peu. La collaboration des Inuits est encore une fois indispensable pour surveiller l'efficacité des efforts planétaires visant à réduire les émissions de mercure dans l'environnement et à protéger la santé des Nunavimmiut.

De la part de nous tous et de nos organismes : un grand merci !

Elena Labranche, présidente du CNSN, au nom des membres du Comité de la nutrition et de la santé du Nunavik.

Mélanie Lemire, titulaire de la chaire de recherche Nasivvik et professeure adjointe à l'Université Laval, au nom de Gina Muckle, Pierre Ayotte, Chris Furgal, Amanda Boyd, Richard Bélanger, Michel Lucas, Catherine Pirkle, professeurs à l'Université Laval, à la Trent University, à la Washington State University et à l'*University of Hawaii at Manoa*.

Sarah Kalhok Bourque, présidente du Programme de lutte contre les contaminants dans le Nord, Affaires autochtones et du Nord Canada, au nom du Comité de gestion du Programme de lutte contre les contaminants dans le Nord.

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Sarah Kalhok Bourque, Chair - Northern Contaminants Program, Indigenous and Northern Affairs Canada, on behalf of the Northern Contaminants Program Management Committee.

MOBILIZING KNOWLEDGE THROUGH A NETWORK OF INUIT EDUCATIONAL LEADERS AND RESEARCHERS: BILINGUAL EDUCATION IN INUIT NUNANGAT

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Becky Tootoo (Government of Nunavut)
Shelley Tulloch (University of Prince Edward Island)

HQP

Naullaq Arnaquq, Doctoral Student (Government of Nunavut)
Cathy Lee, Doctoral Student (University of Toronto)
Jupeeka Hainnu, Research Associate (Community of Clyde River)
Nunia Qanatsiaq, Research Associate (Government of Nunavut)

ABSTRACT

Mobilizing Knowledge Through a Network of Inuit Educational Leaders and Researchers: Bilingual Education in Inuit Nunangat is an innovative research initiative using digital technologies to harness the expertise of Inuit and non-Inuit parents, educators, researchers and collaborators to develop and share effective, research-supported, bilingual education strategies across Inuit Nunangat. Bilingual education that builds on research knowledge as well as knowledge held in Inuit communities is critical to the future economic, cultural and linguistic success of Inuit in Canada. It contributes to student learning at the school and post-secondary levels in the educational system and through this contributes to the strength and vitality of Inuit society. The development of a bilingual, responsive Inuit workforce, well-prepared for current and future economic opportunities is vitally important at this time. Using a grassroots, community-based approach, this initiative is poised to make a significant contribution to the well-being and sustainable future of Inuit in the Canadian Arctic.

KEY MESSAGES

- Each of the Inuit land claims regions have mandates (some stronger, some weaker) for Inuit-controlled education systems.
- Each also has the mandate to preserve, protect, and promote the Inuit language.
- Each region in Inuit Nunangat is pursuing these mandates in different ways, including through bilingual education. Alongside a great deal of hope, Inuit express concern that the efforts to date are not yielding the desired results.
- Academic research results about bilingual education in general and in Inuit Nunangat in particular over the past thirty years have yielded consistent findings as to its benefits and underlying principles for effective delivery, while also identifying ongoing problems in its implementation.
- According to the literature, effective delivery of bilingual education across Inuit Nunangat depends on six pillars:

  1. first and foremost, bilingual education must be embedded in an excellent, well-run and well-resourced education system;
  2. curriculum and practices must build on existing language practices and expand opportunities for language learning;
  3. curriculum, materials, learning spaces, teachers, and environments must affirm and build on identities and cultures;
  4. leadership, teachers, and curriculum must be sensitive and responsive to their specific sociopolitical and linguistic contexts;
  5. understanding and support must exist at all levels, from parents through to government, as well as leadership from people specifically equipped to pursue the goals of bilingual education; and
  6. efforts towards reclamation of language, culture, and lifelong learning must reinforce and reflect efforts in K-12 schooling.

- Analysis of the effectiveness of bilingual education must take each of these pillars into account.
- National, local, regional, and Inuit Nunangat-wide circumstances and needs must be considered when determining which of the six pillars (above) need to be emphasized, where, and by whom in order to improve the effectiveness of bilingual education in Inuit Nunangat.
- Educating and supporting Inuit educators and Inuit educational leaders has been a foundational strategy to improving education in Inuit Nunangat, from the beginning of Inuit self-determination negotiations, and continues to be today.

- Inuit educational leaders have deep knowledge about the promising practices in bilingual education, and are the cornerstone to the implementation of effective bilingual education; however time, distance, and language are barriers to effective knowledge mobilization.
- Effective bilingual education across Inuit Nunangat is a long-term project that must have support across all six pillars, at multiple levels, and from all stakeholders.

OBJECTIVES

From April 2016 through to March 2017, we continued to pursue the three objectives set forth in our original proposal, approved in November, 2014:

1. Facilitate informed dialogue among Inuit educational leaders, parents, community groups, teachers, administrators, curriculum developers, policy makers and scholars regarding current challenges, successes, and promising avenues for enhancing bilingual education in Inuit schools and communities;
2. Analyze, synthesize and compare the recent and relevant scholarly literature related to legislation, policies, and promising practices in bilingual education in Inuit Nunangat; and
3. Mobilize and disseminate knowledge based on evidence-based practices in bilingual education with relevant application to Inuit Nunangat, including creation of short informational videos that act as learning modules targeted at the public, parents, teachers and all decision makers.

KNOWLEDGE MOBILIZATION

- Six presentations at scientific conferences (Inuit Studies Conference (St. John's, NL); COHERE (Sydney, NS); ArcticNet ASM (Winnipeg, MB) and four upcoming papers (WIPCE);
- Revision and submission of two peer-reviewed journal articles;
- Revision of six multi-media modules from Arviat and Inuit leaders' fieldwork, redesigned to maximize accessibility and uptake;
- One short video profiling Jason Annahatak, a bilingual language role model and educational leader from Nunavik;
- One short video profiling language revitalization efforts in Nunastiavut;
- 14 blog posts about the Network, bilingual education, and Inuit educational leaders, including the voices of Inuit educational leaders;
- Mentoring 23 northern research partners,
- Development and sharing of "A Framework for Effective Bilingual Education in Inuit Nunangat"
- Development and online sharing of "A Timeline of Inuit Bilingual Education";
- Development and sharing of a comprehensive bibliography of research dealing with bilingual education relevant to Inuit Nunangat; and
- Information session for students and instructors of the Nunatsiavut Inuit Bachelor of Education program and a representative of the Nunasiavut Government.

INTRODUCTION

Bilingual education (Inuktut and English/French) education is critical to educational engagement and outcomes in Inuit Nunangat (National Committee on Inuit Education, 2011). Land claims and self-government agreements across Inuit Nunangat have opened possibilities for alternatives to the assimilationist policies and institutions that have undermined Inuit language, culture, and well-being.

These agreements have further affirmed Inuit's right to manage their own educational systems.

Canadian Inuit's right to education in Inuktut was first recognized in Nunavik in 1964, and entrenched in the James Bay Northern Quebec Agreement in 1975. Since 1971, Northwest Territories policies have allowed for Inuktut mother tongue education. The Inuvialuit Final Agreement (1984) created the Inuvialuit Social Development Program to address ongoing Inuit-specific concerns in education and maintenance of traditional practices. among others. In Nunavut, the right to Inuktut language education is affirmed by the Inuit Language Protection Act (2008). Nunavut's Education Act (2008) mandates a strong model of bilingual education. The Labrador Inuit Land Claims Agreement (2005) recognizes Inuit's right to use Inuktut and established the Nunatsiavut self-government with authority over Inuit education.

School administrations in each region have made efforts to actualize Inuit's right to learn Inuktut alongside a national language. In Nunavut and Nunavik, where most Inuit still learn Inuktut as the mother tongue, efforts have included strong mother tongue education from Kindergarten to Grade 3, with efforts to expand Inuktut learning through to Grade 12. Students in Nunavik must pass Grade 12 final Inuktut exams to complete their provincially-recognized high school diploma. In Nunatsiavut, the Inuvialuit Settlement Region, and some western Nunavut communities, where Inuktut is less frequently the mother tongue, efforts have been made to introduce Inuktut immersion programs. School-based efforts are reinforced by community efforts supporting lifelong learning, including early childhood programs, land or culture-based programs, and others.

Despite these acknowledged rights and efforts, parents, youth, teachers and others across Inuit Nunangat are increasingly concerned that young people have inadequate opportunities to achieve high levels of bilingualism. Knowledge and use of Inuktut are decreasing. As children struggle at school, a tendency has been to blame bilingual education, rather than see it as part of the solution, concerns explicit in Nunavut's controversial Final Report of the Special Committee to Review the Education Act (2015), which suggests weakening Nunavut's commitment to Inuktut education; they are also implicit in parents' choices in not choosing Inuktut immersion for their child when available.

International research also supports the desirability and effectiveness of bilingual education for students from any background. Research Canada has documented that English mother-tongue students in French immersion schools in Québec and Ontario can achieve bilingual fluency and literacy as well as equivalent or superior academic performance to their monolingual peers (Cummins, 1998). Maori, Hawaiian, Mohawk, and Navajo case studies take these findings further, showing how Indigenous students benefit from immersion education in their ancestral language as a vehicle for language reclamation and as a way of recreating culturally affirming schools that support student perseverance and success (May, Hill, & Tiakiwai, 2006; Reyhner, 1990; Todal, 2003).

Mother tongue and culturally-responsive education has long been established as a promising model, particularly for students from minority communities who may experience multiple barriers to feeling welcome and thus learning and persevering in schools (UNESCO, 1953; Thomas & Collier, 2002). Rigorous research spearheaded by the Kativik School Board over twenty years in fourteen Nunavik communities consistently demonstrated that Inuit students who had Inuktut as their language of instruction from Kindergarten to Grade 3 had higher self-esteem, greater knowledge of Inuktut, and stronger or comparable knowledge of English than their peers educated in the English language stream (Taylor & Wright, 2003). These results are repeated in bilingual education programs across the world, evidence that education in two languages leads to greater proficiency in both languages. Research with post-secondary students also confirms that a grounding in one's identity, culture, and language supports persistence in college and university (Fuzessy, 2008).

The challenge, then, is to achieve a synthesis of the expressed desire for robust bilingualism in Inuit Nunangat, identifying what research has demonstrated about bilingual education in the larger context, and suggesting and communicating practices that may enable them to come together. Research conducted to date via the Akuttujuuk network suggests a need for informed public discourse and activism about the contribution of effective bilingual education to student success to challenge the perception of a sub-section of the population that believes (against research evidence) that English-language education will lead to greater student success.

ACTIVITIES

From April 2016 to the present, the Akuttujuuk research team has engaged in the following activities aimed to address the challenge outlined in the Introduction above.

Enhanced Online Presence

In 2016-17 we modified and extended the Akuttujuuk online presence to achieve broader engagement, including

- maintaining the private FaceBook Group;
- establishing an open Akuttujuuk FaceBook group to widen and extend the reach of the private group, in partnership with "Foundations for Student Persistence and Success in Inuit Nunangat" project);
- maintaining the Akuttujuuk Blog, extending contributions, and initiating a blog redesign; and
- maintaining and monitoring the Akuttujjuuk Channel on Isuma TV.

Field Research

The purpose of field research carried out in 2016-17 was to broaden the reach of the Akuttujuuk network from Nunavut to Nunavik and Nunatsiavik.

Nunavik (June 2016)

In consultation with local researcher and Network member, Mary Joanne Kauki, we planned field research in Kuujuaq and Puvirnituq to document practices in bilingual education and language leadership in Nunavik. This included work relating to the Avataq Cultural Institute's 2012 report, Illirijavut (That which we treasure), as well as a broader documentation of ways in which bilingualism is being achieved and maintained. As part of the field research we planned to meet with Jason Annahatak, director of post-secondary education for the Kativik School Board in Montréal.

At the last minute, the local researcher and Network member leading the Nunavik portion was forced to withdraw. As she was the key contact for the work in Kuujuaq and Puvirnituq, we were unable to complete that portion of the travel. We were, however, able to meet with Jason Annahatak and gained a valuable perspective both on the impact of K-12 bilingual education on the post-secondary experiences of Kativik residents and the experiences of an Inuk who was successful in reclaiming his first language, Inuktut.

Subsequent conversations with Eliana Manrique, Assistant Director of Research at the Kativik School Board reviewed research priorities relating to bilingual education in Nunavik as identified in consultation with the Kativik School Board Commissioners who represent each community. These include 1) How is early bilingual education impacting later Math outcomes? 2) How are students' early and later literacy impacted by initial Inuktut instruction in syllabics as opposed to roman orthography?

These two priorities are beyond the immediate scope of this project; however, there is room for further discussion with the KSB which may be able to partially support a subproject to specifically address them. Until then, our coverage of Nunavik is limited to conversations at conferences and via published sources, including the Facebook groups and Akuttujuuk blog.

Nunatsiavut (October 2016; March 2017, in anticipation of next field trip)

Through ongoing dialogue with Jodie Lane, Education Manager for the Nunatsiavut Government, we identified the Nunatsiavut Inuit Bachelor of Education cohort as emerging educational leaders who will shape the potential for bilingual education in Nunatsiavut where the right to control its own education system has not yet been taken over from the province. A partnership with Memorial University has enabled Nunatsiavut Inuit to take an Inuit-specific bachelor of education degree while living in Goose Bay.

Under the instruction of Dr. Sylvia Moore, they are discovering and creating what an Inuit-specific school system for Labrador might look like, and are expected to play leadership roles when Nunatsiavut does take control of its education system. In addition, the IBEd students are the first cohort to take the Labrador Inuktitut Training Program (LITP). LITP is an innovative, extensive, communication-based language learning program developed by the Nunatsiavut Government to revitalize the language among adult speakers.

Following phone and email consultations with Jodie Lane and Sylvia Moore, we met with the instructors and students of the IBEd/LITP in October, 2016 to discuss the aspects of their journeys as emerging Inuit educational leaders and emerging bilinguals that they might like to profile for Inuit in other regions. In February/March 2017 we plan to travel to Goose Bay to interview and video IBEd students onsite. Their story provides an important perspective on bilingual education in Inuit Nunangat, as the extreme language shift towards English requires first teaching the adults/teachers how to speak in Inuktitut before teaching others.

Meetings and Workshops

- Meeting and video interview with Jason Annahatak, director of post-secondary studies at Kativik School Board (June, 2016). Parts of the interview have been edited for posting to the Akuttujuuk.ca website.
- Meetings and video filming with Jodie Lane (Nunasiavut Government), Sylvia Moore (MUN), and students of the Inuit Bachelor of Education Program (IBEd) during the Inuit Studies Conference in St. John's, NL in October, 2016.
- Face-to-face Akuttujuuk team meetings held at Charlottetown, PE in August 2016, the Inuit Studies Conference in St. John's, NL, October 2016, and at the ArcticNet ASM in Winnipeg, December 2016; the final meeting will take place at WIPCE in July, 2017.
- Ongoing teleconferences between team members; phone calls between academic team members and members of the Akuttujuuk network; phone calls between team members and Inuit organizations.

Knowledge Synthesis

- Bibliography of Publications Relevant to Inuit Bilingual Education is an exhaustive list of the research literature relevant to bilingual Inuit education broken down by all four regions of Inuit Nunangat and by Urban, Alaskan, and Greenlandic Inuit, multiple regions, and global indigenous contexts. A final section lists relevant theoretical sources. The bibliography will be of interest to all scholars, researchers, and policymakers working in this field.
- A critical analysis and synthesis of the material in the Bibliography of Publications (above) has led to the development of a succinct six-pillar framework outlining coherent principles for effective bilingual education in Inuit Nunangat. Aimed at a wider audience including educators and other practitioners, A Framework for Effective Bilingual Education in Inuit Nunangat is accessible at the project website http://akuttujuuk.ca/literature-review.
- Final versions of 6 short bilingual (Inuktut/English) multimedia presentations connecting

the six pillars of the Framework with community practices and initiatives.

- The project website (http://akuttujuuk.ca) has been rethought and is continually being revised and updated to better share resources and encourage comments from network members and the interested public.
- Two panels at WIPCE will bring together multiple partners from various regions and perspectives for roundtables on themes of (a) lifelong bilingual learning and (b) supporting resilient Inuit educators. It is expected that these panels will lead to two further journal articles.
- The final synthesis component of this project included critical discourse analysis (Johnson, 2011). Critical discourse analysis was used to assess the explicit and implicit messages, goals, and audiences of Inuit language-of-education policies from the four Inuit regions. It was also used as a tool for analyzing different language policy texts and their relation to prior and following discourse. Key findings to date include:
    - » Current processes and outcomes of bilingual education in Inuit Nunangat need to be understood in light of power relations, ideologies about language, bilingual learners, and education, as well as in light of the shifting bilingual context and history of schooling in the North;
    - » Public and professional discourse about bilingual discourse (e.g., among teachers, parents) reflects ongoing misunderstandings about the processes and outcomes of bilingual education (e.g., Special Committee to Review the Education Act, 2015);
    - » Parents, educators, and policy makers sometimes consider the multiple goals of bilingual education (effective learning; language reclamation; capable citizens) as in competition, when in fact research shows they are mutually supportive. In particular, the perception that teaching English earlier will necessarily lead to better English proficiency is widespread, but consistently contradicted in research that shows effective transfer of proficiencies from one language to another;
    - » Some language-in-education policy documents show clear and deliberate influence from community consultations and research, e.g Kativik School Board research and policy; Martin's (2000) and Corson's (2000) language-of-instruction papers that influenced the Education Act. Other language-in-education policy-related documents seem to go against research;
    - » New theoretical developments in the study of bilingual education between 2000-2015 are insufficiently represented in legislation, policy, and public discourse, although some teachers are intuitively implementing practices that such developments support; and
    - » Changing and heterogenous language practices in homes, and lack of understanding in schools and on community committees of children's home language use creates additional challenges in establishing and implementing effective school language policies, particularly when discourse focuses on "mother tongue".

Our ongoing critical discourse analysis provides an additional tool to evaluate the flow of ideas and knowledge about bilingual education in Inuit Nunangat and the relative empowerment of Inuit as leaders and participants in discourse that leads to sound policy changes; a paper on critical discourse analysis related to bilingual education in Inuit Nunangat is in preparation.

RESULTS

Our research asked the question, "Under which circumstances are Inuit educational leaders and researchers empowered to generate and communicate, as well as access, evaluate and apply various types of knowledge about quality bilingual education to improve educational outcomes in Inuit Nunangat?" The research question came from Inuit educators' expressed desire for ongoing professional development and a professional network for furthering their practice. The activities described above created frameworks for reciprocal generation, communication, and interpretation of knowledge about bilingual education.

Online Presence

Based on patterns of use in 2015-16, we de-emphasized the use of the Knowledge Forum collaborative online environment in 2016-17 and concentrated on broadening and enhancing the use of Facebook and the Akuttujuuk.ca blog platform. We have also monitored and compared access to multimedia posted to Isuma.tv and YouTube.

We have continued to maintain the private Akuttujuuk Facebook group. In 2016-17 it had 24 members (three southern researchers and 21 Inuit educators, 20 from Nunavut, 1 from Kativik) and 44 posted discussions. We found the private Akuttujuuk Facebook group a useful tool for facilitating networking and ongoing communication between the Nunavut MEd graduates who often feel isolated as one of only two or three Inuit educational leaders in their communities. We have also found it useful for Network members to inform each other of significant events in bilingual education and their own activities.

Despite being a closed group with membership restricted to those agreed upon by all other members, the members have been reluctant to go beyond surface-level exchanges. Deeper critiques and responses to issues in bilingual education have been shared through private emails and phone calls between researchers and Network members, and in face-to-face meetings, but not on the private Facebook group. Comments from network members, as well as issues identified through the literature review (Arnaquq, 2008; Fyn, 2014; Kauki, 2015), suggest that some Inuit educational leaders feel disempowered from taking a public stance, either because they have already said the same thing so many times and not been heard, or because they have been censured for speaking up. These concerns effectively block their empowerment as locally-anchored Inuit scholars of education who would be most effective at creating, interpreting, and disseminating understandings about bilingual education in ways that have real impact in Inuit Nunangat. Concerns about silencing and being heard remain avenues for further investigation.

Regardless of its limitations, Facebook is an almost ubiquitous platform across Inuit Nunangat, to say nothing of globally. To see whether an open group focusing on issues relevant to Inuit education, we launched an open Facebook group in partnership with the "Foundations for Student Persistence and Success in Inuit Nunangat" project — https://www.facebook.com/groups/1015166698627494/. Eighteen members, Inuit and non-Inuit, from across Inuit Nunangat and southern Canada enrolled in less than a month, but it is too early to say more at this point.

In 2016-17, the online tools used by the Akuttujuuk network have continued to facilitate ongoing networking and collaboration between Inuit educational leaders and the university-based team. However, they have not to date led to the breadth or depth of activity that would show they are truly empowering tools for Inuit-driven knowledge generation, at least, in and of themselves. Our experiences in the Nunavut Masters of Education program showed us that face-to-face meetings were essential for sustaining the online component of knowledge exchange (Wheatley, Tulloch, & Walton, 2015) and we wonder if the lack of predictable in-person meetings between the broader network is a limiting factor in this network. A subsequent sister ArcticNet project, "Foundations for Student Persistence and Success in Inuit Nunangat", is building on this finding by prioritizing a FTF forum that includes Inuit educational leaders from all four regions.

Field Research

In the context of this project, field research includes both opportunities to meet and work with collaborators from Inuit Nunangat in southern contexts and their home communities.

Attendance at conferences, for example, combined with the time to work on presentations together beforehand has been an effective tool for amplifying Inuit educational leaders' voices as researchers and scholars. Building on work from 2015-16 which saw three Inuit Network members presenting co- or single-authored papers, 2016-17 saw contributions from nine Network members, seven of them Inuit.

As Inuit network members, all women, are busy educators and leaders with full-time jobs outside of academia, the partnerships with a university-based team are helpful for navigating processes of abstract submission, travel arrangements, conference registration, and so on. The presence of these Inuit scholars at these meetings is of crucial importance for continuing to create spaces where Inuit see other Inuit as scholars generating and communicating new understandings based on academic research.

These in-person meetings recall the importance of establishing and maintaining the relationships that are at the core of Indigenous methodologies (Smith, 1999). The formal meetings and informal meals together enabled us to build the trust necessary for collaborative and empowering work.

The in-person meetings at conferences have also contributed new relationships which will support network expansion into other areas. For example, the relationship with Jodie Lane, Nunatsiavut representative on the National Committee on Inuit Education, was established through meeting at several conferences and has greatly facilitated the field research scheduled to take place in Nunatsiavut in the final quarter of this year. Supplemented by her interview as an Inuit educational leader, her perspectives on bilingual education in Nunatsiavut are incorporated into Network deliverables.

Community-based field research in 2016-17 has been inspired by the work in Arviat led by network member, Nunia Anoee-Qanatsiq and supported by the university-based team. It brought together Inuit who are recognized as leaders due to degrees (MEd graduates), leadership positions (District Education Authority Board members), or family/community roles (Elders and parents). Even at the data collection level, this process mobilized "grassroots knowledge-making" (Canagarajah, 2005) as these knowledgeable and implicated community members shared with each other what they consider to be working in bilingual education, as well as their concerns.

Results were contextualized within network dialogue about the Truth and Reconciliation Commission's findings on the disruption of parental and community leadership in education, and the National Committee on Inuit Education's focus on family engagement. They were also contextualized in the history and current practices of bilingual education in the four Inuit regions. These findings were presented at the international Etudes Inuit Studies conference in October 2016, and have been accepted for publication by AlterNative, a peer-reviewed journal with the mandate to amplify the voices of indigenous researchers.

The six multimedia presentations based on the Arviat data and interviews with Inuit elders are being released through the Akuttujuuk channel on isuma.tv, YouTube, and the Akuttujuuk website (e.g., http://akuttujuuk.ca/bilingual-learning-modules/rich-language-environments/). They are intended for further use by families, schools, DEAs, etc., and for viewing by Inuit across Inuit Nunangat. They can be used on a standalone basis or integrated into a single presentation as they were for a session on bilingual education to be used by the Coalition of DEAs. It should be noted that a pilot multimedia presentation distributed over isuma.tv has received 672 views since its posting in January 2016.

This smaller scale, intensive, and mainly in-person collaboration was a successful example of Inuit educational leaders being empowered to generate, interpret, and disseminate knowledge about bilingual education. The Inuit research leader, Nunia, owned this part of the project and exercised a strong voice conducting the interviews, interpreting the data, creating the videos, preparing the co-authored journal article and presenting the research results at the 2016 ArcticNet ASM. She expressed satisfaction throughout the process, and pleasure at seeing the work come together in forms that will reach larger audiences.

The work continues to be disseminated in forms that maintain the voices of the Inuit educational leaders who participated. The journal article quotes them extensively (although in English translation). The video snippets are particularly effective in that audiences will see faces, gestures, and expressions, and hear the speakers using their own words in Inuktut. In these ways, video dissemination has emerged as an effective tool for amplifying the voices of Inuit educational leaders who wish to share perspectives and experiences in bilingual education, especially with other Inuit audiences.

As the modules are released, we will be able to track and evaluate how frequently they are accessed, and whether they are indeed effective tools for Inuit receiving knowledge.

Although with more limited scope to date, similar approaches were adapted for field research in Nunavik and Nunatsiavut and are described in the Activities section above.

DISCUSSION

Colonization has interrupted and blocked the transmission of Inuit Qaujimajatuqangit (Inuit ways), including intergenerational transmission of the Inuit language (QTC, 2012; Rowan, 2014; Tagalik, 2009a). The interruption of intergenerational transmission of Inuktut happened earlier in the most westerly and easterly Inuit communities (Patrick & Shearwood, 1999). The crucial role of parents as children's primary educators was deliberately undermined by the residential schools, with ongoing effects on language learning and educational outcomes (TRC, 2015). Ongoing implicit colonizing practices (TRC, 2015) need to be halted, and parents' inherent leadership role restored (Smith, 1995) to establish stronger foundations for effective bilingual education in Inuit Nunangat (Aylward, 2007; Aylward, 2009; Berger, 2009; Fyn, 2014; Salokangas & Parlee, 2009).

All four Inuit regions in Canada have land claims agreements that create space for Inuit-driven action toward bilingual education. Where they exist, legislation and policies favour Inuktut language-of-instruction, at least from Kindergarten to Grade 3 (e.g. Kativik School Board Policy on languages of instruction, 2003; Northwest Territories Education Act, 1995; Northwest Territories Department of Education, Culture, and Employment Departmental Directive on Aboriginal language and culture-based education, 2004; Nunavut Education Act, 2008). Protective measures in the land claims, laws, and policies are effective measures against repeating overtly assimilationist agendas (Hornberger, 1999).

Principals, teachers, parents, and students deeply impact language-of-instruction practices, sometimes in support of and sometimes counter to existing policies (Aylward, 2010; Lewthwaite, 2007; May et al., 2004; Wyman, 2004). The most effective implementation of true bilingual education occurs in schools with strong Inuit leaders or culturally-sensitive, long-term Northerners (Lewthwaite, 2007; Tulloch et al., in press; Walton et al., 2014).

Inuit teachers fluent in Inuktut is a core component of bilingual education (Cram, 1995; Patrick & Shearwood, 1999). Nunatsiavut is laying a foundation for Inuit-controlled education through teacher training with a strong language-learning component (Anderson & Moore, 2016). Nunavut, Nunavik, and Alaskan Yup'ik educators have had opportunities to participate in Inuit/Yup'ik)-specific post-graduate programs (Marlow & Siekmann, 2013; Wheatley, Tulloch, & Walton, 2015). Ongoing specialized professional education equips teachers to understand the patterns and needs in emergent bilinguals' learning, to ensure cultural and linguistic sensitivity among teachers, and for Inuit teachers to obtain certifications required to access leadership positions (O'Donoghue, 1998).

CONCLUSION

Responding to concerns expressed in the National Strategy for Inuit Education (2011) and building on the desire of graduates of the Nunavut MEd for a network to support their continued professional growth and contributions to better education for Inuit, this project has identified the pillars on which effective bilingual education for Inuit Nunangat must be built, explored online and face-to-face strategies for building a network to address them, and highlighted salient initiatives and practices. Effective bilingual education across Inuit Nunangat is a long-term goal that must acknowledge local and regional contexts and perceptions. We believe that this project has contributed to a deeper understanding of the principles on which effective bilingual education in Inuit Nunangat is based, how those principles may be communicated, debated, and critiqued, and how they have found life in current practices.

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FOUNDATIONS FOR STUDENT PERSISTENCE AND SUCCESS IN INUIT NUNANGAT

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ABSTRACT

This research project addresses two interrelated questions, following priorities articulated by the Amaujaq National Centre for Inuit Education: 1. What is contributing to Inuit students' persistence in or withdrawal from school, particularly at grade transitions?; 2. How are students progressing in Inuit schools, what are they achieving, and how is this achievement being assessed? For over forty years, Inuit and allies have worked toward equitable access, assessment, and achievement in Inuit schools. At the same time, statistics, reports, and community observations show that further efforts are required to support Inuit students to reach their potential, and have their achievements accurately acknowledged (e.g., Auditor General, 2013; Berger, 2006; NCIE, 2011). Through the compilation, synthesis, and contextualization of existing data and initiatives, as well as case studies in selected Inuit communities, this research will contribute to an evidence base from which those working in education can develop and prioritize initiatives to improve equitable access to high quality education in the North. The end result is supporting Inuit students to stay in sch have their learning assessed and recognized in culturally and linguistically appropriate ways.

KEY MESSAGES

- This project is an Inuit-led and partnered research project that is unearthing key insights for policy on how to ensure schools in Inuit Nunangat are fostering student success.
- We are mentoring Northern High Quality Personnel (HQP) through the involvement of two Inuit graduate students and one Inuit undergraduate student. We also hired local researchers for our two case studies this year. Participation in the Inuit Education Forum also provided professional development and networking opportunities for Inuit educators and educational leaders. Northern HQP participate in in each aspect of this project, including research design, implementation, co-analysis, conference presentations, article authorship, and community liaison. Northern HQP are involved from each Inuit region.
- An Inuit Education Forum was held in Nain, Nunatsiavut in February 2017 which brought together 28 Inuit educators from all four regions of Inuit Nunangat. This Forum was organized and facilitated by two other northern HQP. Keynote speakers came from Nunavik, Nunavut, Nunatsiavut, and the Inuvialuit Settlement Region.
- A position paper entitled (re)Visioning Success in Inuit Education highlighting key educational reforms was jointly written by the participants of the Inuit Education Forum.
- A documentary film on the Inuit Education Forum is being produced by our team and the OKâlaKatiget Society (based in Nain, Nunatsiavut).
- We have interviewed individuals in Nunatsiavut, Nunavut and the Inuvialuit Settlement Region who have completed post-secondary education on how their K-12 experience led to their educational success. Nunavik post-secondary students have been invited and will participate in 2017-2018.
- Two case studies were conducted (in Hopedale, Nunatsiavut and Aklavik, NWT) which harnessed information on educational success from a wide range of stakeholders (current teachers, students, graduates, parents, Elders, etc.). Groundwork has been conducted for case studies in Taloyoak, NU and Kujjuuaq, QC in Year 2.
- We have obtained research licenses and established partnerships in Nunatsiavut, Nunavut, and NWT. We have had phone calls and email exchanges with Kativik School Board through 2016 and 2017 to establish the research relationship, and have submitted a proposal to the

Kativik School Board to work closely with them in Year 2.

- We have established relationships with Inuit and Yup'ik teachers and scholars of education in Alaska to contextualize results internationally.
- An environmental scan of existing policies and practices that are working to bring about student success across Inuit Nunangat is underway.
- A literature review has compiled existing knowledge about project themes, as documented by prior research in Nunavik, Nunatsiavut, Nunavut, and NWT.
- Five academic papers have been drafted by our multi-disciplinary and community-partnered team which allows for a holistic understanding of factors contributing to educational success in Inuit.
- Summaries and insights from our research are posted on our Facebook page and on the website akuttujuuk.ca for popular outreach.
- Existing national survey results have been analyzed for trends in student success factors. We are communicating with school boards and Departments of Education regarding the collection of school records data which provide us with another important source of information for evidence-based policy recommendations.

OBJECTIVES

The three main objectives of this project are to:

1. Compile, synthesize and contextualize existing data, knowledge, and practices with regard to indicators of Inuit student retention, assessment, and achievement across Inuit Nunangat;
2. Document and disseminate initiatives, experiences, and perspectives that contribute to Inuit student persistence and success through case studies in Inuit-majority schools that are identified as having high levels of student persistence, and through facilitated conversations with Inuit post-secondary students; and
3. Develop policy recommendations based on our findings for increased student persistence and achievement in Inuit Nunangat using analysis of existing data sources, compilation of school records data and through holding a gathering of Inuit educators from across Inuit Nunangat.

KNOWLEDGE MOBILIZATION

- Plain language community FAQ sheet regarding the project was written and distributed to/via community partners in English and Inuktitut.
- One of our student researchers has written a blog entry on education and the significance of Inuit-led research (http://akuttujuuk.ca/why-do-research-graduate-inuk-student-reflections/).
- One of our student researchers, Kayla Bruce, has created a public Facebook Page to share the results of our research in the future: https://www.facebook.com/groups/1015166698627494/. She is experimenting in the creation of photos with embedded text to augment blog postings and emphasize key messages from research, e.g. https://www.facebook.com/photo.php?fbid=10154883910027317&set=gm.1022777127866451&type=3.
- We are developing plans to transfer information from the Akuttujuuk website from the Mobilizing Inuit Educational Leaders project to this one.
- Presentation on details of this project by Melanie O'Gorman at the University of Winnipeg Knowledge Mobilization Series (Feb. 1, 2017).
- Our team secured two supplementary grants (one from the Social Sciences and Humanities Research Council (SSHRC) and the other from the Global College's (University of Winnipeg) Marsha Hanen Global Ethics and Dialogue

Program) to hold an Inuit Education Forum. This Forum was held in Nain, Nunatsiavut in February 2017 and a position paper was jointly written by participants of this forum for distribution to northern policy makers.

- A film is being produced by Ian Mauro and the OKâlaKatiget Society.
- Melanie O'Gorman attended a workshop in Ottawa on knowledge mobilization hosted by SSHRC entitled "A Successful Shared Future with First Nations, Inuit and Métis Peoples" to introduce our project.
- Melanie O'Gorman attended a workshop in Ottawa on how to produce a high quality op-ed facilitated by Shari Graydon of Informed Opinions.
- Presentations of research results by Tess Miller and Melanie O'Gorman at the ArcticNet ASM (Winnipeg, MB).
- Presentation of research results by Melanie O'Gorman at the Canadian Economics Association Meetings (Antigonish, NS).
- The following presentations will occur at the World Indigenous Peoples Conference on Education (Toronto, July 2017):
    - "Building Resilience in Inuit and Yup'ik Educators" - Lead Presenters: Sheila Wallace and Becky Tootoo; Co-authors: Lena Metuq, Mary Etuangat, Cathy Lee, Sylvia Moore, Fiona Walton, Sandy McAuley, Sabine Siekmann, Patrick Marlow, Sally Samson (co-organized with ArcticNet Akuttujuuk grant);
    - "Strategies for lifelong bilingual learning" -Lead Presenters: Nunia Qanatsiaq Anoee, Sally Samson, Jodie Lane, Mary Etuangat; Co-authors: Cathy Lee, Becky Tootoo, Lena Metuq, Adriana Kusugak, Shelley Tulloch, Sandy McAuley (co-organized with ArcticNet Akuttujuuk grant);
    - "Restoring Roles and Relationships for Effective Education" - Lead Presenter: Diane Obed; Co-authors: Nunia Qanatsiaq Anoee, Heather Ochalski, Becky Tootoo, Sylvia Moore, Cathy Lee, Melanie O'Gorman, Kathy Snow, Shelley Tulloch;
    - "Building Resilience in Inuit Students" - Lead Presenter: Heather Ochalski; Co-authors: Kayla Bruce, Diane Obed, Melanie O'Gorman, Kathy Snow, Shelley Tulloch; and
    - "Male Inuit Identity and Education" – Lead Presenter: Becky Tootoo.
- Research team meetings at ArcticNet ASM (December 2016) and the WIPCE conference (upcoming in Toronto, July 2017). At the WIPCE team meeting next month we will be working on finalizing our academic articles with all members of our team that will be there.
- Shelley Tulloch met with Department of Education officials and Inuit teachers and curriculum developers in Iqaluit and Cape Dorset Nunavut. Shelley Tulloch summarized research project on local radio in Cape Dorset, Nunavut. Consultation to external review of Nunavut Arctic College's Teacher Education Program, based on results to date from this project.
- The Inuit Education Forum was covered on the CBC website at http://www.cbc.ca/news/canada/newfoundland-labrador/inuit-education-forum-nain-1.3981682.
- Team members consulted with local partners and contributed to a letter to the editor in response to Nunavut's proposed *Education Act* changes.
- Shelley Tulloch attended Indigenous Education Forum and Indigenous Teacher Education Conference, April 2017, Winnipeg, MB.
- In collaboration with participants from the Hopedale case associated with the Memorial University Inuit Bachelor of Education Program, we are planning to help IBED students share land based learning lesson activities for teachers on the Akuttujuuk website.

- Kathy Snow was selected to travel on the C3-Voyage in August, and will share theme/concepts developed from the forum and case study, as the ship broadcasts from Cambridge Bay to Kuujjuaq.

INTRODUCTION

Mary Simon, past Chair of the National Committee on Inuit Education, wrote of a vision for Inuit schools that would "graduate bilingual Inuit children with the skills and knowledge to contribute with pride and confidence to the 21st century" (NCIE, 2011, p. 4). Educational attainment in Inuit regions is significantly lower than that in the rest of Canada. For example, in 2012, 58 percent of Inuit aged 18-44 had not completed high school, compared to 11 percent of the non-Aboriginal population in the same age group. Attendance is also an issue in many Northern communities. For example, in 2012 a quarter of students who dropped out of school reported missing school often (Statistics Canada, 2012).

In January 2016, the Amaujaq National Centre for Inuit Education, along with the ArcticNet Centre of Excellence, issued a call for research proposals to identify factors that are supporting or hindering Inuit students from staying and excelling in school. To address these factors, our team of researchers applied for and received funding for the project Foundations for Student Persistence and Success in Inuit Nunangat. Our team of researchers and community organizations is now addressing the following questions:

1. What is contributing to Inuit students' persistence in or withdrawal from school, particularly at grade transitions?
2. How are students progressing in Inuit schools, what are they achieving, and how is this achievement being assessed (including mainstream and Inuit-specific indicators of success)?

Hence our research was initiated by questions raised by the National Committee on Inuit Education. It is informed by and respects Inuit statements of desirable researcher conduct in Inuit Nunangat (Amaujaq/National Committee on Inuit Education, 2013; Arnaquq, 2014). We are using an assets-based approach, respectful of different forms of knowledge and existing expertise in Inuit Nunangat.

In order to address the research questions above, we are compiling, synthesizing and contextualizing practices and policies that are enabling Inuit students to stay in and excel in school. Across the North, innovative teachers, principals and administrators have developed and adapted materials, assessment tools and interventions to meet the needs of Inuit learners. However, in light of high workloads and rapid staff turnover, much of this work remains unknown, undocumented, underutilized and unevaluated. By bringing together what is already known and/or being implemented in each of the four Inuit regions, and by conducting original research into factors which support student persistence and success, our research will create an evidence base from which northern policy makers and educators can develop and prioritize initiatives.

We are analyzing currently-available data and collating other data for future analysis. A great deal of high quality academic research has indeed been conducted on Inuit education (e.g. Aylward 2007, 2009; Berger, 2007, 2009a, 2009b; Berger & Epp, 2007; Berger, Epp, & Moeller, 2006; Lewthwaite & McMillan 2010; Lipka, 1998; Martin, 2000; McGregor, 2012; Nungak, 2004; O'Donoghue et al., 2005; O'Gorman and Pandey 2015; Patrick, 2013; Rodan et al., 2010-15; Taylor & Wright, 2003; Tompkins, 1998, 2004; Tootoo, 2015; Tulloch et al., 2015; Vick-Westgate, 2002; Walton et al., 2010-2015; Walton & O'Leary, 2015). These studies indicate ways in which student success can be fostered by, for example, increasing Inuit leadership and staff in schools (Walton & O'Leary, 2015), developing strong community partnerships (Tompkins, 1998) or developing support materials to help promote Indigenous learning in the classroom (McGregor, 2012). Few studies however are able to capture the entirety of the complexity of successful schools. The academic papers we have written and will publish and disseminate will provide holistic, multi-methods, and cross-regional analysis, contextualized in local and academic knowledge, that allow for this complexity to be confronted.

Experiences in the four Inuit regions show strong points of convergence and divergence, yet opportunities to gather and learn from one another are scarce. Although there is a large literature on the educational situation in particular communities or regions, very little academic research has been produced which draws from experiences across all four Inuit regions. Educational legislation, policy development, curriculum and materials development, teacher training and teacher professional development all occur at regional levels. The National Strategy on Inuit Education (2011) provides a cross-regional vision for Inuit education. The Inuit Education Forum that we held in Nain, Nunatsiavut in February 2017 allowed for dialogue between 28 Inuit educators from Nunatsiavut, Nunavik, Nunavut, and the Inuvialuit Settlement Region. We have also gained in-depth understanding of factors associated with educational success in two case studies (Nunatsiavut and Inuvialuit Settlement Region) and through interviews with Inuit post-secondary students (Nunatsiavut, Inuvialuit Settlement Region, Nunavut). These case studies will be complemented by further data collection in Nunavik and Nunavut. Statistical analysis of factors reported in large scale surveys provides insights into trends across Inuit schools and regions. Comparison and contrast of prior publications on project themes from each region also supports cross-regional synthesis of successes and challenges in Inuit student persistence and success. Contextualization of results in broader Indigenous education trends also supports the development of evidence-based policy recommendations.

ACTIVITIES

July 2016

- In July 2016 our team had a conference call to discuss our work generally and to identify our four case study communities.

August 2016

- In August 2016, Shelley Tulloch, Kathy Snow, Tess Miller, Kate Tillecjek, Fiona Walton, and Sandy McAuley met in Charlottetown, PEI, in conjunction with the Aboriginal Education: Truth & Reconciliation Symposium.
- Creation and maintenance of project "Basecamp" (online project management and team collaboration tool), bringing together all project researchers, student assistants, and community partners (21 active team members).
- Identified, hired, and trained two Inuit students who will work as researchers on the project, Diane Obed (MA student, from Hopedale, Nunatsiavut) and Kayla Bruce (B.Ed. student from Rankin Inlet, Nunavut).
- Inuit Tapiriit Kanatami assigned Heather Ochalski (Project Coordinator, National Committee on Inuit Education) to the project. Heather is also working on a Masters degree related to Inuit Education.
- Identified and hired local researchers/HQP to support specific aspects of the research, including X for the Aklavik case study, Y for the Hopedale case study, Holly Carpenter for Inuvialuit Settlement Region post-secondary interviews and Teevi Mackay for Nunavik post-secondary interviews.

September 2016

- Shelley Tulloch and Kathy Snow spoke with National Committee on Inuit Education to clarify our project's vision and goals.
- Successful submission of grant proposals to secure additional funding for an Inuit Education Forum and resulting documentary film.

October-November 2016

- Developed research and ethics protocols. Ethics approval was secured by the University of Winnipeg and Cape Breton University for all aspects of the project.

- Partnerships established and ethics/licensing secured from the Nunatsiavut government; Labrador School Board; Aurora Research Institute; and Nunavut Research Institute.
- Phone calls and email exchanges with Eliana Manrique, Assistant Director of Research at Kativik School Board. Research proposal submitted to the Kativik School Board (Shelley – submit email and call dates).
- Shelley Tulloch attended the Inuit Studies Conference and concurrent research team meetings; dialogue and collaborative interpretation of data collected to date; collaborative planning for next research stages; three position papers from literature review posted to Akuttujuuk website.
- Literature review completed by Tess Miller on assessment practices in Inuit Nunangat.
- Analysis of the Aboriginal Peoples Survey by Melanie O'Gorman.

December 2016

- Presentations by team members at the ArcticNet ASM (co-authored presentation) and team co-creation retreat in Winnipeg that week.
- Identified, hired and trained a community-based research assistant (Nicole Shuglu) for the Hopedale case study.

February 2017

- Holding of the Inuit Education Forum by our team members and the Nunatsiavut Government.
- Documentary film production by Ian Mauro and the OKâlaKatiget Society based on the Inuit Education Forum.
- Case study of educational success in Hopedale, Nunatsiavut (conducted by Kathy Snow in February 2017).

May 2017

- Identified, hired and trained a community-based research assistant (Rhonda John) for the Aklavik case study.

June 2017

- Presentation of research results (analysis of the Aboriginal Peoples Survey) at the Canadian Economics Association meetings (Antigonish, NS).

On-going

- Identified, hired and trained four non-Inuit students as research assistants on the project – Katharine Klassen (B.A. student in Anthropology at the University of Winnipeg), Shanti Subedar (B.A. student in Anthropology at the University of Winnipeg), Craig Peters (B.Ed. at Cape Breton University) and Maxime le Moullec (B.A. student in Economics at the University of Winnipeg).
- Shelley Tulloch has been speaking to education stakeholders regarding promising practices and policies for an environmental scan.
- Shelley Tulloch, Kathy Snow and Melanie O'Gorman have organized narrative sharing with post-secondary students in Nunavut, the Inuvialuit Settlement Region and Nunatsiavut. Student researchers Kayla Bruce and Diane Obed are in the final stages of conducting these interviews.
- Sandy MacAuley, in consultation with the research team, has been doing further work on the Akuttujuuk website, including developing plans to transfer the site to this project, and disseminate our results using this site.
- We have expanded the blog on the Akuttujuuk website (http://akuttujuuk.ca/blog/) to profile the work of Inuit teachers and Inuit scholars of education. Diane Obed (M.A. Student, Nunatsiavut) and Louise Flaherty (Director of Language and Culture, Nunavut Arctic College)

contributed guest blog entries on their role and vision as Inuit researchers of education. We also profiled the leadership of Velma Illasiak (Principal, Aklavik, NWT) and the Inuit Circumpolar Council's Alaskan Inuit Education Improvement Strategy. (In addition to our project's postings on Inuit education generally, a cognate project continues to post on bilingual education specifically.)

- Kayla Bruce (student research) created a public Facebook page for Inuit educators to share encouragement, resources and promising practices across (https://www.facebook.com/groups/1015166698627494/; this site is in addition to the private Facebook page for Inuit educators under the Akuttujuuk project).
- Networking at national and international conferences, and during fieldwork for other projects, to share research process and elicit ideas from Inuit leaders (e.g. Paul Quassa, Nunavut Minister of Education; John McDonald, Assistant Deputy Minister of Education, Nunavut; Tim McNeil, Deputy Minister of Education, Nunatsiavut; Jodie Lane, Education Manager, Nunatsiavut; Nancy Karetak-Lindell, President, Inuit Circumpolar Council) as well as other researchers of Inuit education (e.g. Paul Berger).

RESULTS

Results from the Inuit Education Forum, case studies, post-secondary interviews, statistical analysis, and literature review/environmental scan all point to ongoing efforts to decolonize education as central to improving students', families', teachers', and communities' experiences of school. Decolonization of Inuit education means reversing the power and privilege embedded in the system at its assimilationist origins, and infusing Inuit education with Inuit ways of knowing, being, and doing.

Inuit control of Inuit education requires Inuit teachers and Inuit school administrators who feel empowered and free to act in leadership roles. Across the regions, cases are documented where Inuit teachers feel like they are unable to express a strong voice, or to exert leadership. Strategies in place to empower Inuit as leaders in transforming school systems include professional development/teacher education that builds critical awareness of past injustice in the school system and creates safe spaces for teachers and pre-service teachers to express and enact resistance.

Building the resilience of all teachers in the school is crucial to fostering a constructive learning/working environment, and continuing relationships, which in turn contribute to safe learning environments in which students are more likely to persist. Strategies to build teacher resilience include professional development and orientations for Inuit and non-Inuit teachers, including opportunities for relationship-building and cultural competence training.

The importance of family support in students' success is well documented in the literature. Our analysis of national statistics, post-secondary interviews, and case studies corroborates the centrality of family. We are deepening understandings of this role by digging into which behaviours from family members are most supportive; how policy can support those behaviours; and which initiatives have been successful (or not) in engaging families.

In our multi-methods, cross-disciplinary approach, we are finding that some of the results from one method contradict results from another method. For example, while the literature review emphasizes the advantages of Indigenous language education, the Aboriginal Peoples Survey results correlate Indigenous language education with lower academic achievement. We are exploring these inconsistencies between smaller scale documentation of promising practices and large scale statistics to see if they may provide evidence of gaps in policy implementation. Although Nunavik and Nunavut have strong policies or legislation for decolonized, Indigenized education, policy and practice may not be in alignment.

Specific results, from specific activities, follow.

- We organized and held an Inuit Education Forum in Nain, Nunatsiavut in February 2017. This Forum allowed for the exchange of insights between 28 Inuit educators, a methodology Canagarajah (2005) calls "grassroots knowledge-making". Inuit and long-term northern teachers have seen what is helping or blocking students. In this Forum, their understanding of what is working in their classrooms and at the school and regional levels was shared, and the focus was on making practical recommendations for educational reform in their communities and schools. As noted above, a report has been written on the insights gained at the Forum and this will be shared with policy makers by the end of summer 2017. The recommendations made at the Forum are summarized below:

    1. Decision-making in schools should be shared to a greater extent as in traditional Inuit culture.
    2. To ensure a larger proportion of teachers are Inuit or long-term northerners, there is a need for an expansion of community-based teacher training programs and reforms in how teachers are hired.
    3. Improvements are needed in the working climate/culture of schools.
    4. An expansion of innovative efforts that support parents in their interactions with schools is needed.
    5. Culturally-relevant curricula should be further developed across Inuit Nunangat.
    6. Land-based activities are seen as critical to ensuring culturally-relevant schooling in each region.
    7. A greater proportion of class time should be devoted to Inuktitut instruction.
    8. Schools in small communities need all the supports – for both students and teachers - that schools in large communities have in order for students to thrive.
    9. Educators need more frequent opportunities to gather with other educators from across Inuit Nunangat to share their experiences.

- Completion of two case studies – In Year 1 we conducted two case studies – one in Hopedale, Nunatsiavut and one in Aklavik, Inuvialuit Settlement Region. These have harnessed insights from educational stakeholders (teachers, parents, high school graduates and Elders) on the determinants of educational success in these communities. Individual reports on these case studies are being written. Key findings were:

    » The policy of 'social passing' (passing students to the next grade level even if they are unprepared) has little support among parents and teachers.

    » A culturally-relevant curriculum requires teaching materials and lesson plans if teachers are to successfully implement it.

    » Inuktitut/Inuvialaktun instruction must be supported by language revitalization efforts in the home and community – language instruction in schools is insufficient.

    » Teachers often deal with a wide range of academic preparedness among their students, requiring increased assistance from teaching assistants and increased hiring of instructors.

    » Students often graduate from high school without the requisite courses and knowledge to go onto post-secondary education – increased hiring of teachers and parental engagement is needed to arrest this trend.

- Literature review by Tess Miller on academic assessment for Inuit and non-Inuit students across Canada. The purpose of this literature review is to provide an overview of literature reporting on different types of assessment and corresponding outcomes previously used to measure achievement of Indigenous peoples.

Miller finds that of the three territories, the Yukon is the most advanced in terms of student assessment. They have a full program of large-scale assessments that begins in kindergarten and measures children's readiness for school with the Foundation Skills Assessment program. When focusing on educational attainment, students in the Yukon are at par, or slightly above the Canadian population.

- Analysis of the Aboriginal Peoples Survey by Melanie O'Gorman on factors associated with truancy, academic performance and educational attainment and the production of two academic papers based on this analysis. This Statistics Canada dataset is the largest that is available for Inuit Nunangat and provides information on a wide range of factors thought to be associated with academic achievement. Two academic papers have been written on this analysis however key findings are summarized below:
    - For respondents in grades 7-12 access to the internet at home is associated with an approximately 10% lower chance of missing school.
    - For younger age groups (those currently in grades 1-12), if the school has contacted the parent there is a lower chance that the child will report grades higher than 70%. However, if the parent is proactive in their contact with the school or reports that they feel the school is communicating well, the child is more likely to have high grades. Having a sibling who has dropped out of school for this age group is also associated with a 6-17% lower chance of reporting high grades.
    - For those in grades 1-6, being taught an Indigenous language is associated with a 6% higher chance of obtaining high grades. For those in grades 7-12, cultural participation is associated with a 12% higher probability of having obtained high grades. For those aged 45+, cultural participation is associated with a 15% lower probability of having obtained high grades, and being taught an Indigenous language is associated with a 10% lower chance of obtaining high grades.

Overall we find that being taught an Indigenous language is associated with lower academic achievement, truancy, lateness and lower educational attainment. One cannot attribute causality to this result however it could be that instruction in an Indigenous language is either of low quality (due to the scarcity of fluent instructors), that such instruction is being removed too early or that it is interfering with children's English fluency. Indigenous language instruction is necessary for cultural revitalization in the north and the right to have one's child educated in an Indigenous language is enshrined in the Inuit land claims agreements. This result could however suggest that more resources are needed for Inuktitut-instruction teacher training programs or an evaluation of the effectiveness of bilingual education programming is needed. Peer effects and having a sibling drop out of school aid are also important for explaining the gap between Inuit and non-Inuit regions in educational attainment, arriving for school on time and attendance at school. This suggests, not surprisingly, that children are heavily influenced by those in their peer group, and therefore there are likely threshold effects at play – once attendance and dropout fall below a certain level, we may see positive influences on other children that will cause attendance and graduation rates in the north to improve significantly. This does not suggest any particular policy recommendation however it suggests that any policies associated with educational achievement are much more important.

These results will be workshopped with community partners and Inuit researchers during meetings held concurrently with the World Conference on Indigenous Education, and then released in a series of publications targeted to journals specializing in Indigenous education; Indigenous-led research; Indigenous policy; and educational policy.

DISCUSSION

Year 2 will be an extremely busy one with at least two more case studies to be conducted and our research results to be submitted for publication. The Taloyoak case study has been confirmed and will be conducted in September 2017. The papers that will be submitted for publication soon are:

1. "Understanding Educational Achievement in Inuit Nunangat: An Analysis of the Aboriginal Peoples Survey" by Melanie O'Gorman – likely to be submitted to Canadian Public Policy.
2. "Indigenized Education: Failed implementation failing students?", by Melanie O'Gorman, Shelley Tulloch, Kathy Snow and Heather Ochalski – likely to be submitted to the International Journal of Educational Policy or Indigenous Policy Journal.
3. "'Modern' pedagogy? Makerspaces and Inuit Qaujimajatuqangit" by Kathy Snow – likely to be submitted to the Canadian Journal of Native Education.
4. "Harnessing the Knowledge of Inuit Education Leaders" by Kathy Snow, Melanie O'Gorman, Heather Ochalski, Jodie Lane, Shelley Tulloch. To be submitted to: Education in the North Special Issue: 'Teacher Education in the Arctic' (Volume 25 Issue 1 May 2018).
5. "Decolonizing Schooling through Conscientization, Resistance, and Transformative Action in Indigenous Teacher Education" by Sylvia Moore, Shelley Tulloch. To be submitted to Education in the North or InEducation.
6. "Assessing Literacy and Numeracy in Inuit Communities" by Tess Miller – journal to be determined.
7. "Gender Differences in Inuit Schools: Engaging Inuit Boys" by Shelley Tulloch and Becky Tootoo. To be submitted to AlterNative.

These articles are drafted, and will be workshopped with Inuit community partners and HQP during our project writing workshop held concurrently with attendance at WIPCE.

The Inuit Education Forum was an important event which expanded our network of researchers and practitioners which we will continue to harness even after this ArcticNet project has ceased.

One of the themes that has come out in discussions with individuals during the case studies and environmental scan is the need for evidence-informed advocacy for policy change. That is, education stakeholders are eager to hear the results of studies such as ours which systematically examines the determinants of success in schooling. As we move forward, we will disseminate all of our research results to schools, DEAs, policy makers and school boards to aid them in prioritizing initiatives, applying for funding for special programming and changing policy to improve educational outcomes.

Our team is working very well together and a lot of the groundwork for our main activities is now complete. We expect to achieve the majority of our objectives by the end of the grant period.

CONCLUSION

By the end of Year 2 of this grant, our project will have addressed two interrelated questions, following priorities articulated by the Amaujaq National Centre for Inuit Education:

1. What is contributing to Inuit students' persistence in or withdrawal from school, particularly at grade transitions?
2. How are students progressing in Inuit schools, what are they achieving, and how is this achievement being assessed?

This project will harness knowledge of existing initiatives that are taking place across the north to ensure Inuit students stay in school, excel in learning and have their learning assessed in culturally and linguistically appropriate ways. We look forward to sharing this synthesis widely across the north in order to support improved education policy and practice in Inuit Nunangat.

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HOUSING, HEALTH, AND WELL-BEING ACROSS THE ARCTIC: REGIONAL, LOCAL, AND FAMILY PERSPECTIVES

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ABSTRACT

Access to adequate housing has been a social, ecological, and health problem in Inuit communities since the movement toward sedentary living began in the 1950s. A large proportion of Inuit households live in inadequate housing conditions that contribute to the severity and the frequency of respiratory health problems, especially among children, infectious diseases, social and mental health problems in the Arctic. Studies have shown that "rehousing", i.e. moving to a new house, may improve health directly or indirectly through psychosocial pathways. The project brings together Inuit and Western epistemologies (ways of knowing) and methodologies (ways of doing) to assess the impacts of housing conditions on individual, family, and community health and well-being in Nunavut, Nunavik, and Nunatsiavut. This interdisciplinary project will study four inter-related components: 1) the health and well-being impacts of moving to a newly built social housing unit; 2) the experience of housing transitions on the lives of Inuit families moving into a) new social housing units in Nunavut and Nunavik, and b) an Inuit designed energy-efficient multiplex unit in Nunatsiavut; 3) the definition of adequate housing, overcrowding and its influence on health and well-being from Inuit perspectives; and 4) the role of housing conditions for fostering and sustaining healthy ageing. For Component 1, all adults aged 18 years and older in single-person or family households on the waitlist for social housing in selected communities will be invited to participate in survey interviews. Questionnaires will assess: housing conditions; mental and physical health, and stress; psychosocial factors; socioeconomic information; and health of children aged 3 to 36 months. For Components 2, 3, and 4, qualitative methods employed will be conversation based. Specific methods include focus groups and individual interviews. These methods will be applied to explore participants housing conditions, experiences during their housing transition, their overall sense of health and wellness, meanings of home and of adequate housing, and ageing in the home. This project was developed through ongoing collaboration between university researchers, Inuit/northern researchers, and Inuit partners/organizations. Assessing the health and wellbeing impacts of moving to a new house is timely as all regions are currently restructuring their long-term housing strategies. Identifying housing conditions (perceived and objective) and psychosocial factors influencing health and well-being could suggest points of interventions and facilitate the targeting of housing resources more effectively. Qualitative descriptive and thematic work will help identify specific pathways to health and illness associated with housing while also developing indicators and models that are relevant to, and draw form, Inuit culture and historical experience. This type of project has been identified as required to build effective evidence-based cases justifying greater investments in affordable housing in the Arctic.

KEY MESSAGES

- Follow-up data collection was conducted in Nunavik in May 2016 and in three communities in Nunavut in November 2016; data collection was scheduled about 18 months after participants moved into a new house. Follow-up data for the other Nunavut communities will be collected in April 2017.
- We conducted an evaluation of a housing prototype in Quaqtaq that was co-designed with Inuit.
- In the upcoming months, additional projects will be conducted to:
    - » understand Inuit families' experience of housing transitions into new social housing units (2017) and an Inuit-designed multiplex unit in Nain, Nunatsiavut (2017; 2018);

» understand cultural practices and meanings of adequate housing and overcrowding (2017); and

» explore the role of housing in fostering healthy aging (2017).

OBJECTIVES

The project Housing, health, and well-being across the Arctic: Regional, local, and family perspectives (hereafter Housing and Health in the Arctic) consists of five interrelated components, each at different stages of completion (Table 1).

KNOWLEDGE MOBILIZATION

Several knowledge mobilization activities were conducted in Year 2 of the project.

Knowledge transfer activities with partners

- In March 2016, 2-day meetings were held in Iqaluit and Kuujjuaq with partner organizations to analyze and interpret results of baseline data collection.
- Four short reports (one-pagers) of baseline data were prepared and shared with partner organizations. The one-pagers focusses on results for the following themes: psychosocial and structural conditions of housing, community and neighborhood conditions, and health status. An undergraduate student was recently recruited to explore data visualisation methods to produce infographics for the one-pagers, to improve the

Table 1. Project components and status to completion.

Components	Status
1.1. Assess the impacts of moving to a newly built social housing unit on Inuit health and well-being, and the mediating role of PSF;	Ongoing; follow-up data collection completed in April 2017
1.2. Assessing indoor air quality (pilot project)	Initially Y1; then re-scheduled for Y2 where we encountered hurdles and had to re-orient this project.
3. Document the experience of housing transitions on the lives of Inuit families moving into a) new social housing units in Nunavut and Nunavik and b) an Inuit-designed multiplex unit in Nain, Nunatsiavut and in Quaqtaq, Nunavik from which additional funding was received from the SSHRC partnership Living in Northern Quebec;	a) Because of delay in housing construction, data collection will be conducted in Y3: 2017 b) Because of delay in housing construction, data collection will be conducted in Y3: 2017. Baseline data collection in Quaqtaq, Nunavik in December 2016; analysis ongoing.
4. Define adequate housing and overcrowding and their influences on health and well-being from Inuit perspectives;	Year 3, as schedule
5. Assess the role of housing conditions in fostering and sustaining healthy aging in the Arctic.	Year 3, as scheduled

dissemination of results from this project to community members.

Presentation to policy-makers

- Presentation to Minister Geoffrey Kelley, Secrétariat aux Affaires Autochtones, Gouvernement du Quebec. Housing, health, and well-being across the Arctic: Regional, local, and family perspectives. October 2016.
- Presentation to the Standing Senate Committee on Aboriginal Peoples. Housing for health and well-being in the Arctic. By video-conference. May 2016.
- Polar Knowledge Canada. Northern Housing Infrastructure. Panel presentation on socioeconomic dimensions of housing, Specific contribution: Housing as a social determinants of health. Ottawa, Canada. February 2016.

Presentation at scientific conferences

- Riva, M. Housing, health and well-being in the Arctic: the importance of psychosocial factors. NUNAMED conference, Nuuk Greenland. October 2016.
- Riva, M. Fletcher, C., Vachon, G. Housing, health and well-being in the north: Understanding, imagining, mobilizing. Forum Santé Nord/ Northern Health Forum. Quebec City, Canada. June 2016.
- Riedlsperger, R., Bell, T., Riva, M. Sustainable Housing in Northern Canada: Learning from Nunavik and Nunatsiavut. ArcticNet Scientific Meeting. December 2016, Winnipeg, Manitoba.

INTRODUCTION

This report details activities conducted in Year 2 of the project. As this project comprises five different components, activities and results and reported together for each of the components. The current report focusses on activities conducted between April 1st 2016 and up to March 31th 2017.

ACTIVITIES AND RESULTS

Component 1: Assess the impacts of moving to a newly built social housing unit on Inuit health and well-being, and the mediating role of psychosocial factors (PSF)

<u>Study design and sample size.</u> The project uses a prospective study design with assessments before and after moving to a new house. Baseline data was collected one to six months before participants moved to a new house, i.e. in the Fall 2014 in Nunavik, and in Spring 2015 in Nunavut. Of the 289 participants we interviewed at baseline, about 60% moved to a new house. Follow-up data collection was conducted about 18 months after participants moved to a new house. Follow-up data collection was completed in May 2016 in Nunavik and in November 2016 in three communities in Nunavut; data collection in the remaining 3 communities in Nunavut will be conducted in April 2017. A total of 53 people participated in Nunavik and 22 so far in Nunavut, for a participation rate of 62.5%. For the remaining three Nunavut communities, we anticipate interviewing 32 people, if the same participation rate is achieved.

<u>Data collection.</u> In each community, a team of two research assistants (RAs) collected data. They were assisted by one local Inuit researcher (IR) who helped with contacting participants, scheduling interviews, and assisting with administering questionnaires in Inuktitut or Inuinnaqtun when requested by participants. Data collection took place in a neutral environment (e.g. rented room at the municipal office). Two questionnaires were used to collect data at baseline and follow-up. The household questionnaire was administered to the person whose name was on the waitlist; only one person per household responded to this questionnaire. All participants responded

to the individual questionnaire. The questionnaires were developed in collaboration with Inuit partner organizations. They were pilot-tested with Inuit living in Quebec City, in Nunavik and Nunavut.

Data analysis. Longitudinal data analyses are ongoing, and will be completed once we have access to all the follow-up data; these will start in May 2017. Other data analyses done in the past year include:

- Preliminary data analyses presented in last year's report were finalized, such as:
  - » Production of descriptive statistics and frequencies for all variables.
  - » The internal consistency of scale-based variables has been examined in preliminary analysis (e.g. psychological distress, psychosocial factors [PSF], perceived community/neighborhood conditions, etc.).
  - » Chi-square have been conducted to examine whether PSF vary between participants living in overcrowded vs. not overcrowded houses.
- Regression analysis are currently being conducted to examine whether psychosocial factors vary between participants living in overcrowded vs. not overcrowded houses.
- Analyses comparing perceived and objective crowding are currently ongoing, including regression analysis and sensitivity analysis.
- Preliminary regression analysis to examine associations between housing conditions and health outcomes.

Scientific papers in preparation. Three scientific articles are forthcoming. Analysis are at different stages of completion. Manuscripts will be first submitted to the advisory committee of the project, and then to peer-reviewed journals.

Riva, M., Dufresne, P., Perreault, K., Fletcher, C., et al. Housing in the Canadian Arctic: structural, psychosocial and spatial dimensions.

This article describes housing conditions of participants to the 'baseline' interview of Component 1. The focus is on structural housing conditions such as repairs needed, overcrowding, and affordability; psychosocial factors associated with the house environment, e.g. perceived control, privacy, satisfaction; and on the spatial dimension of housing, i.e. perceived community conditions such as social cohesion and safety. Results are presented separately for Nunavik and Nunavut. Analyses are completed; we anticipate submitting the manuscript to the Canadian Geographer, by March 31st, 2017.

Results show that the socioeconomic circumstances of participants involved in this project reflects the socioeconomic hardship experienced by many in the Arctic and the high cost of living. Housing instability, e.g. moving homes often and time on waitlist add to the financial struggles and may collectively contribute to chronic stress. Although everyone met at baseline in this study was 'housed', about one third of participants reported having offered shelter to someone who had no place to live. This speaks to concern about widespread hidden homelessness across the Canadian Arctic, where extreme climate conditions 'limit' visible homelessness. With regard to housing adequacy, 29% and 44% of participants, respectively in Nunavik and Nunavut, reported their house to be in need of major repairs. Apart from the need of major repairs, the most frequent problems reported by participants were related to air quality or isolation from the cold during winter. Data on overcrowding indicates that 50.9% of households in Nunavik, and 64.5% in Nunavut were overcrowded conditions.

Roughly half of participants in both regions expressed positive perceptions in relation to identity, privacy/retreat, and satisfaction items of the psychosocial dimension of housing. Most respondents thought they were safe and had good relationship with people in the house, and were satisfied with the location of the house within the community. Notions of space and control were the most problematic domains of the psychosocial dimension. With regards to the spatial dimensions of housing, our data indicate an overall positive portrait of the spatial dimension of housing in both Nunavik and Nunavut regions, although respondents from Nunavut tended to express positive perceptions of community conditions in a slightly higher proportion. Amidst the harsh conditions of living in the North, it is known that Inuit have maintained a strong sense of community.

Even though people from Nunavut report significantly less favorable situations than people in Nunavik on several socioeconomic and structural characteristics (money situation, income, employment, mobility, time on waitlist, overcrowding, repairs needed, mold inside the house), these differences do not reflect on psychosocial aspects as only a few factors were reported differently between Nunavik and Nunavut regions (for example, there is no difference between regions in satisfaction with the house). As for spatial dimension, when there were differences between regions, Nunavut tend to have higher proportion of people who have positive perceptions.

Riva, M., Dufresne, P., Fletcher, C., et al. Housing in the Canadian Arctic: Differences in psychosocial factors based on crowding.

This paper examines whether psychosocial factors (PSF) associated with the house environment varies by overcrowding. Analyses are completed; we anticipate submitting the manuscript to the Housing Studies, by March 31st, 2017. Results show that people living in overcrowded dwellings generally hold less favorable perceptions of their housing environment, e.g. they report significantly less control, privacy, and satisfaction.

Pepin, C., Riva, M., Dufresne, P., Fletcher, C., et al. Objective or subjective crowding: which is more important for health among Inuit populations?

This article will contribute to the theoretical and empirical debate on measurement of crowding and overcrowding for research in the Arctic, and more widely for research on housing and health among Indigenous populations. Analyses are ongoing, and will be finalized with the follow-up data later this Spring. This paper is lead by a PhD student involved in the research project. This manuscript will be submitted to Health & Place.

Component 1.2: Measure indoor air quality in Nain, Nunatsiavut

Because of events that were outside the control of the research team, fieldwork for this sub-project had to be cancelled.

However, a policy-oriented manuscript is currently being produced by Rachel Kohut, an undergraduate Law student at McGill University, supervised by Profs Jill Baumgartner and Scott Weichenthal. Given the recent national housing consultations, Ms. Kohut has been writing an article on housing in Nunatsiavut from a policy and legal perspective, namely at the intersection of indoor air quality standards, and the right to a healthy environment and an adequate standard of living. To do so, she will discuss international conventions that lack teeth in Canadian legislation, and the jurisdictional ambiguity that exists in Canada regarding housing inspection and maintenance, particularly for Indigenous communities. The case of Nunatsiavut allows for a unique discussion of these issues and intersections, while also presenting possibilities of how to better implement building codes and inspect homes in remote and rural corners of the country. The paper is currently in redaction and will be submitted by the end of 2017.

Component 3: Understand Inuit families' experience of housing transitions into a) new social housing units; and b) an Inuit-designed multiplex unit

Due to housing construction delays, this component is delayed to Year 3, but scientific activities have started to realize it.

a) *Understand Inuit families' experience of housing transitions into new social housing units.* Understanding Inuit families' experience of housing transitions into new social housing units is integrated in Karine Perrault's PhD thesis in Public Health at Université de Montréal (UdeM); she is co-supervised by Mylene Riva and supervised by Louise Potvin (UdeM; co-research on ArcticNet project).

Qualitative data collection will be conducted with participants involved in Component 1, who agreed to be contacted for in-depth discussion about their experience of housing transition. We aim to interview a total of 24 families. Interviews will explore personal significance of moving to a new home and family's perception of their health, wellness, and perceived quality of life post-move; and will document participants' housing trajectory, allowing a deepened understanding of the process of becoming and unbecoming housed over time. Data will be collected using narrative-based interviews.

b) *Understand Inuit families' experience of housing transitions into Inuit-designed multiplex unit.* This sub-component explores whether Inuit co-designed housing has discernible effects on the well-being of residents. In addition, we will document the experiences of those involved in the implementation of the co-designed housing unit, from design to construction and performance over time. This component in integrated in Rudolf Riedlsperger PhD thesis on sustainable housing in the Arctic, and is conducted in collaboration with Professor Trevor Bell. Both are in the Department of Geography at Memorial University in St. John's Newfoundland.

Data collection for this project was conducted in November-December 2016. Data analysis is currently underway, but we can report the following preliminary results.

Preliminary results. Preliminary analysis of interviews reveals that residents in Quaqtaq perceive Inuit co-designed housing to have positive effects on their well-being. In particular, the co-designed housing units appear to be conductive to social interactions among family, friends, or community members. This is in part due to the layout of the units, which are designed to accommodate or foster (traditional) sociocultural activities. Residents also identified possibilities to further improve the co-designed housing units, including, for example, better accomodation for persons with reduced mobility. A preliminary analysis of the interview data reveals that residents associate their new homes with feelings of safety (or security) and independence.

Preliminary analysis of interviews conducted with decision-makers informs us that the process of co-designing homes can be divided into four broad phases, which are interdependent and overlapping: (1) Funding, (2) planning, (3) implementation, and (4) monitoring, all of which require coordination among various actors. Results also suggest that main drivers of Inuit co-designed housing include a functioning culture of communication and collaboration, willingness to move beyond tried and true standard practices, and the ability to invest in housing that reaps long-term benefits as opposed to short-term savings. Barriers stem from limited financial resources, the immediate need for housing to meet high demands, and the lack of data or information on best practices on Inuit co-designed housing.

Interviews were also conducted with charrette participants (members of various Nunavik communities), who revealed they were generally pleased with the process of the design charrette, which took place in Kuujjuaq in 2012. Some of their input was taken up and implemented in the Quaqtaq model homes. However, participants expressed dismay with

the communication (or lack thereof) that has taken place since the charrette. They felt excluded from the process, and expressed interest in being more pro-actively involved, especially if their expertise were to be sought again in the future. As community members are important contributors to Inuit co-designed housing, it is crucial to consider long-term strategies for maintaining their input throughout all phases of the process.

Component 4: understand cultural practices and meanings of adequate housing and overcrowding

This project is scheduled for realization in 2017. No activities to report at this time.

Component 5: Explore the role of housing in fostering healthy aging

Component 5 is embedded in Marie Baron, PhD thesis in Community Health at Université Laval. Data collection is scheduled for the Fall 2017.

DISCUSSION AND CONCLUSION

Looking back on Year 2 of this project, progress towards objectives is certainly being made, despite housing construction delays and other events outside the control of the research team. Three scientific articles are close to completion, and several graduate students are involved in the different components of the projects. Year 3 of the project will produce results for all components; reporting on results will be more extensive in next year's report.

ACKNOWLEDGEMENTS

This project evolves within a collaborative research environment between university researchers and partners as well as involving participative inquiry where partners work closely with researchers at all stages of the process. The structure of governance of this project therefore reflects this philosophy.

The overall structure of the project is composed of the principal investigator, the university co-researchers, the research coordinator, students and research assistants, and Nunavut and Nunavik partner organizations. University researchers and the partner organizations are on equal footing as research priorities will be determined through discussion and will strive to obtain consensus.

We have established a process for dissemination and publication of research results, whereby all research results and knowledge generated by the project is presented, discussed and approved by the partner organizations, university researchers, and the Nunavik Nutrition and Health Committee before they are disseminated externally to the general public, including scientific publications and conferences.

DIARRHEAL ILLNESS AND ENTERIC INFECTIONS AMONG YOUNG CHILDREN IN NUNAVIK AND NUNAVUT

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HQP

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ABSTRACT

An unprecedented outbreak of severe parasitic diarrhea caused by *Cryptosporidium* species was identified in Nunavik (northern Quebec) in June 2013 and has since spread to several villages. The same parasite was recently also found in the Qikiqtani region of Nunavut. *Cryptosporidium* is usually considered to be a problem in tropical countries, so finding it in the Arctic is quite unexpected. This is important because it mostly affects young children and is linked with long-term harm in other populations (growth stunting and possibly cognitive delay). Chlorination of surface water does not kill *Cryptosporidium*, and no effective drug treatment is available in Canada. More broadly, little is currently known about the frequency of diarrheal disease in people living in the Canadian Arctic, but the conditions allowing for cryptosporidiosis also favor transmission of many other intestinal infections. The objective of this project is to define the magnitude of diarrheal infections in Arctic communities, to assess their impact on child growth and development, and to propose interventions for prevention. We expect that intestinal infections are an important cause of preventable serious illness in the North. We plan to look for harmful microbes in stool from preschool-age children in two large Arctic communities. Results from this study will be presented to parents and other community members. The information gained from this project will directly help communities to make policies that will prevent infectious diarrhea, and ultimately help children to reach their full potential.

KEY MESSAGES

- The recent recognition of widespread human cryptosporidiosis in Nunavik and Nunavut raises concern about possible long-term effects on growth and development of children in Inuit communities.
- Repeated enteric infections are thought to be highly prevalent in these regions, but very little is known about the spectrum of causative agents or whether this enteric disease burden has a negative impact on the developmental trajectory of affected Indigenous children.
- This project aims to quantify the burden of enteric infections of childhood, measure their impact on child growth and development, and will inform subsequent community-adapted interventions that will prevent enteric infections and help children reach their full potential.
- Conventional diagnostics are often not feasible in remote settings. Most of the remote Indigenous communities of northern Canada have little or no local access to conventional microbiology testing for infectious diseases.
- This deficit is thought to contribute to ongoing disease transmission and the very high rates of enteric infections, sexually transmitted infections, and tuberculosis found in these communities.
- This project aims to implement near-care rapid molecular diagnostics in existing health structures, and demonstrate their feasibility of use and added value in remote northern settings.

OBJECTIVES

The objectives of the project remain unchanged.

Overall objective: To improve the health of young children in Canadian Arctic communities in partnership with local health authorities and parents/guardians. This will be accomplished by quantifying the burden of enteric infections of childhood, measuring their impact on child growth and development, and will inform subsequent community-adapted interventions that will prevent enteric infections and help children reach their full potential.

Specific aim 1: Determine the incidence and prevalence of (i) intestinal infections and of (ii) diarrhea in terms of age, sex and seasonality.

<u>Specific aim 2:</u> Identify the infectious causes of the diarrhea using appropriate laboratory methods.

<u>Specific aim 3:</u> Estimate the effect of intestinal infections and/or diarrhea on growth (using growth indicators of height-for-age (stunting) and linear growth velocity).

KNOWLEDGE MOBILIZATION

- Two peer-reviewed manuscripts published:
  - » Yansouni CP*, Pernica JM, and Goldfarb D. Enteric Parasites in Arctic Communities: Tip of the Iceberg? Trends Parasitol. 2016; 32(11):834-838.
  - » Thivierge K, Iqbal A, Dixon B, Dion R, Levesque B, Cantin P, Cédilotte L, Ndao M, Proulx J-F, and Yansouni CP*. *Cryptosporidium hominis* is a newly recognized pathogen in the Arctic region Nunavik, Canada: Molecular characterization of an outbreak. PLOS Neglect Trop Dis 2016;10(4):e0004534.
    - * This work was awarded the Dr. Donald A. Henderson Prize for Outstanding Global Health Research 2016; McGill University Global Health Programs.
- Two presentations at scientific meetings:
  - » Yansouni CP; Mettre à Jour Notre Conception du Laboratoire Diagnostique pour les Régions Éloignées - L'exemple des Infections Entériques dans l'Arctique. 84e Congrès de l'ACFAS, Montreal, Canada (May 2016, Montreal; Main Audience: Researcher, Invited).
  - » Harper, Sherilee, C. Yansouni, D. Goldfarb, A. Cunsolo, S. Weese, A. Bunce and J Sargeant; Foodborne, Waterborne, And Zoonotic Enteric Disease: Ecohealth Surveillance For Environmental Health; ArcticNet Annual Scientific Meeting 2016 Conference Program - Poster Presentation Abstracts, Winnipeg, Canada 5-9 Dec 2016.
- Student presentation at Global Health Night, McGill University:
  - » Demir K & Yansouni CP; Studying the Impact of Childhood Enteric Infections in the Canadian Arctic - A Behind-the-Scenes Look at Participative Research and Earning Community Trust; McGill Global Health Night 2016.
- Five broadcast interviews:
  - » Radio Interview, CBC Radio 1 "As it Happens" (National, English). Available at http://www.cbc.ca/player/play/2687739352/.
  - » Television Interview, APTN National News (National, English). Available at http://aptn.ca/news/2016/05/04/tropical-parasite-found-in-nunavik/.
  - » Radio Interview, Radio Canada International (International, English). Available at http://www.rcinet.ca/en/2016/05/01/tropical-parasitic-infection-found-in-the-arctic/.
  - » Radio Interview, CBC Radio North (National, English/Inuktitut). Interview May 2016. No link available.
  - » CTV News (National, English). Available at http://www.ctvnews.ca/health/stomach-parasite-emerges-in-indigenous-communities-in-far-north-1.2878669.
- Six print interviews:
  - » Print Interview "Zoonotic Infections in the Arctic" by Elie Dolgin; Nature (UK) – article proposed for forthcoming special issue 2017.
  - » Print Interview; "Disease experts tracking tropical parasite in the Arctic" by David Murphy; Nunatsiaq News (Iqaluit, Nunavut); 23 March 2016. Available at http://www.nunatsiaqonline.ca/stories/article/65674disease_experts_tracking_tropical_parasite_in_the_arctic/.

  - La Presse. (Montreal, Canada). Available at http://www.lapresse.ca/actualites/sante/201604/28/01-4975956-un-parasite-tropical-dans-larctique-quebecois.php.
  - Le Devoir. (Montreal, Canada). Available at http://www.ledevoir.com/societe/sante/469559/mysterieuse-eclosion-d-un-parasite-tropical-au-nunavik.
  - The Montreal Gazette. (Montreal, Canada). Available at http://montrealgazette.com/news/local-news/montreal-disease-experts-tracking-tropical-infection-in-the-arctic.
  - Print Interview, High North News (Nord, Norway). Available at http://www.highnorthnews.com/.
- Seven presentations to community stakeholders in Kuujjuaq and Iqaluit:
  - Daycare Board of Directors meetings in July 2016 and Dec 2016 (Kuujjuaq).
  - Parent information night on 30 Nov 2016 (Kuujjuaq).
  - Qikiqtani General Hospital Lunch and Learn rounds Nov 2016 (Iqaluit).
  - Communicable Disease unit, Nunavut Department of Health Services Nov 2016 (Iqaluit).
  - Hospital laboratory staff Dec 2016 (Kuujjuaq).
  - Public Health Department 29 Nov 2016 (Kuujjuaq).
  - CLSC family education workers 28 Nov 2016 (Kuujjuaq).
- Introduced track on Enteric Infections in remote settings - Course co-Director: Global Health Diagnostics – McGill Summer Institute, Montreal, Quebec (13-17 June 2016); 100 participants, 37 countries.
- Translating knowledge into policy by sitting on the provincial committee on diagnostics implementation (including for Northern Health Centres): "Comité scientifique permanent des analyses de biologie médicale", Institut national d'excellence en santé et en services sociaux (INESSS), Quebec.

INTRODUCTION

Challenging living conditions in Arctic communities cause myriad health concerns, among which infections figure prominently.[1] For example, infections are among the top three causes of Inuit infant death.[2, 3] Diarrheal diseases are of particular concern in the Arctic because conditions favouring their transmission are common, such as significant overcrowding[4], specific food practices, and frequent use of untreated surface water.[5] Globally, one in ten child deaths results from diarrheal disease in the first five years of life.[6] Repeated exposure to enteric pathogens has been strongly associated with functional and structural disruption of the intestinal mucosa, a process termed environmental enteropathy.[7] Enteropathy is believed to be an important cause of growth failure in children, and areas with the highest rates of enteropathy coincide with those having the highest rates of childhood diarrhea. Although short-lived diarrheal episodes (i.e. an isolated episode of three days or less) do not appear to affect long-term growth, prolonged diarrhea (i.e. lasting 14 days or more) is strongly associated with reduced linear growth velocity (ranging from slow growth, to reduced adult height, to stunting in severe cases).[8-11] Parasitic infections caused by species of *Giardia* and *Cryptosporidium* are among the most common causes of childhood diarrhea in areas with high rates of environmental enteropathy and linear growth delays.[12, 13] The presence of enteric parasites in asymptomatic children is also an independent predictor of growth delay.[14] Further, emerging evidence suggests enteric infections in young children (either symptomatic or asymptomatic) may have sustained effects not only on growth but also other aspects of development such as cognition.[15] Worryingly, these effects are exacerbated by food scarcity, which is reported by 24-46% of households surveyed in Nunavik and Nunatsiavut.[16]

Unfortunately, little is currently known about the epidemiology of diarrheal disease in people living in the Arctic. Recent survey data found the highest self-reported incidence of acute enteric illness in the developed world is in Northern Canada [17]. The Nunavik Inuit Health Survey 2004 of people from all 14 coastal villages found that 10% of people reported having diarrhea in the previous month.[18] Alas, this type of data is subject to recall bias, underestimates the incidence of enteric infections by only describing those with diarrhea, and provides no information on the etiologic spectrum of disease.

To address this void, our team retrospectively performed molecular testing of all stool specimens submitted to the Qikiqtani General Hospital in Iqaluit, Nunavut over an 18-month period. We found that many enteropathogens – particularly *Cryptosporidium* species - were not being detected by conventional testing procedures and therefore were not being reported to public health authorities.[19] In the same year (2013), an unprecedented outbreak of severe parasitic diarrhea caused by *Cryptosporidium* species was identified in Nunavik. It built momentum rapidly, spreading from a single village to ten villages in its first six months. In the course of investigating this outbreak, it has become clear that intestinal parasites are highly prevalent in Nunavik, with nearly 30% of individuals submitting stool for microscopy diagnosed with a reportable parasitic infection during the outbreak. In our recently published description and molecular characterisation of this outbreak [20], we established that transmission followed an anthroponotic pattern and that the outbreak strain was a subtype Id of *C. hominis,* which has very rarely been identified in Canada previously. Given that the majority of people affected by the outbreak are young children and that enteropathogens are associated with linear growth delay and possibly impaired neurocognitive development, the implications of these findings are important for affected communities.[7, 21] The emergence of *Cryptosporidium* in Arctic communities in Nunavik and Nunavut demonstrates a pressing need to investigate its epidemiology, which likely differs in several respects with previously described outbreaks in southern regions because of differences in customs, water infrastructure, and Arctic ecology.

ACTIVITIES

Time frame: April 2016 to January 2017

Research: In the year 1 report, we detailed how the post-award period focused on planning study logistics, solving problems in the planned Nunavik study site, solidifying partnerships with northern colleagues, and intensively seeking outside funding partners to ensure the feasibility of the project as described. Since then, we have successfully implemented the study in Kuujjuaq and Iqaluit, and have integrated several aspects of the study in regular health structures such that the project has a positive impact on the broader community. Recruitment of children, their families and collection of stool specimens began in Dec 2016 in Kuujjuaq. Start of recruitment in Iqaluit is projected during Feb-Mar 2017.

1. Establishing outside funding streams for project viability

- ArcticNet funding used to leverage no-cost extensions for RI-MUHC startup funds.
- ArcticNet funding used to leverage two investigator-initiated research Grants:
    - » BD Biosciences (Canada) “BD Collaboration: Diarrheal Illness and Enteric Infections among Young Children in Nunavik and Nunavut” [Total value CAD$ 70,000 in-kind reagents].
    - » BioMérieux “Using state-of-the-art diagnostic strategies to prevent morbidity from enteric infections in remote areas where conventional diagnostics fail” [Cash CAD$ 57,450, equipment CAD$ 50,000, Reagents CAD$ 100,800: Total value CAD$ 208,250].

  - Two current proposals to outside funders (requesting in-kind and cash contributions) and currently submitted (SeeGene diagnostics and MUHC foundation).
  - Dr. Yansouni obtained a Chercheur-boursier clinicien - Junior 1 Career Award; Fonds de recherche du Québec – Santé (FRQS) 2016-2020, as well as a 3-year Subvention d'établissement de jeune chercheur clinicien $45,000 operating grant.

2. Research protocol and REB submission

- The study protocol was finalised in spring 2016 and submitted to REB and RI-MUHC, where several revisions were requested before study approval was obtained in Sept 2016.
- The protocol for expanded testing in Iqaluit has been approved by the Nunavut research Institute (NRI) and has been approved.
- In Nunavik, a change in the mandate of the Health and Nutrition committee has left a vacuum for the evaluation of scientific protocol in the region. To address this, we are currently dialoguing with the Nunavik Regional Board of Health and Social Services to ensure that local stakeholders are involved in the approval and monitoring of the study.

3. Developping the Case Report Forms, Electronic Data Capture, and data management architecture

- Study data collected and managed using REDCap electronic data capture tools hosted at McGill University Health Centre - Research Institute. REDCap (Research Electronic Data Capture) is a secure, web-based application designed to support data capture for research studies, providing: 1) an intuitive interface for validated data entry; 2) audit trails for tracking data manipulation and export procedures; 3) automated export procedures for seamless data downloads to common statistical packages; and 4) procedures for importing data from external sources.
- We developed REDCap instruments for demographic, anthropometric, microbiologic data tailored to each study site, and performed pilot testing using a tablet interface. This allows for offline data capture and subsequent transmission when internet is available.

4. Materials purchase

- Most of the anthropometric equipment, lab supplies, and other study equipment were purchased this year.
- All supplies and equipment were identified and delivered to specified locations (eg specimen refrigerators in Kuujjuaq daycares (Figure 1-2), lockboxes for cards and tablets, and coolers for specimen transport (Figure 3)). A -80degC freezer was dedicated to the study at the Kuujjuaq hospital (Figure 4), as was a specific supply storage area for consumables.
- Lab supplies and equipment for molecular subtyping of protozoan parasites were purchased.

5. Determining molecular methods to be used in study

- As detailed in last year's report, our original plan was to perform all microbiological testing as large batches every four months at McMaster and McGill.
- The nearly CAD$ 400,000 difference between funding requested and funding awarded required us to reconsider our planned methods.
- Moreover, results of our CIHR-funded planning meeting "Building an Arctic Enteric Infections Research Agenda" in Iqaluit 22-23 March 2015 clearly indicated that infrequent batch testing in the South would not engage communities to participate in the research.
- We used two mitigation strategies: (1) We sought synergies with local health system in Kuujjuaq to adapt our protocol to the molecular diagnostic platform best suited

Figure 1. Iqitauvik Daycare Centre at dusk, Kuujjuaq, Nunavik.

to their current needs, and actively assisted in the implementation of the BD Max platform there. (2) We engaged diagnostics industry partners with investigator-initiated research proposals.

- In Kuujjuaq, BD Bioscience (Canada) will provide CAD$ 70,000 in reagents for the BD Max.
- In Iqaluit, where no local molecular testing for enteric infections is currently available, BioMérieux will provide a BioFire® FilmArray instrument as well as CAD$ 100,800 in reagents. This Health-Canada approved platform will allow results to guide clinical management and could easily be implemented in the routine clinical lab in Iqaluit.
- In both research locations, same-day clinical results will now be available.

6. Implementing near-care molecular diagnostics for routine use in Kuujjuaq

- PI (Yansouni) appointed "Designated Microbiologist Consultant for Nunavik".
- Advised laboratory coordinators on priority technologies to implement for improving care in remote northern communities. This led to the

Figure 2. Refrigerator used for short-term storage of stool specimens at the Tumiapiit Daycare Centre, Kuujjuaq, Nunavik, before being transported to the laboratory.

implementation in December 2015 of the BD Max PCR platform for rapid molecular detection of several pathogens.

- Although this platform is implemented for clinical use, implementation in Kuujjuaq will allow for study microbiology to be performed locally by hospital staff, and results can be used clinically to guide the management of people found to harbour infections during the study. This is a major asset to the community as well as to the study.
- Validation of the BD Max platform identified certain weaknesses that will be palliated by performing additional testing in Montreal for parasites and viral pathogens.

7. Nunavut study site preparation – Iqaluit

- Co-PI (Goldfarb) working with partners in Iqaluit to arrange study logistics.
- Medical Advisory Committee (MAC) of the Qikiqtani General Hospital and Territorial

Figure 3. Lockbox for logbook and computer tablets and coolers used for specimen transport between daycare and laboratory.

Diagnostics Advisory Committee decided to implement the BioFire® FilmArray instrument for routine use for a trial period as part of this study.

- Much energy spent on expediting interface between this platform (to be used in the study) and the hospital laboratory information system.
- Instrument verification is underway and should be complete by late Feb 2017.

8. Identification of research personnel

- Identification and retention of adequate personnel (to recruit patients with informed consent, to administer monthly questionnaires, and to help with anthropometric assessment is one of the more challenging aspects of this project. Nonetheless, integration with local stakeholders has yielded positive contacts and all positions are currently filled.

9. Recruitment

- An evening information session was held on 28 Nov in Kuujjuaq and several families agreed to participate in the study. It is anticipated that these families will encourage broad participation in the study, with the aid of the family-liaison workers in each daycare site.

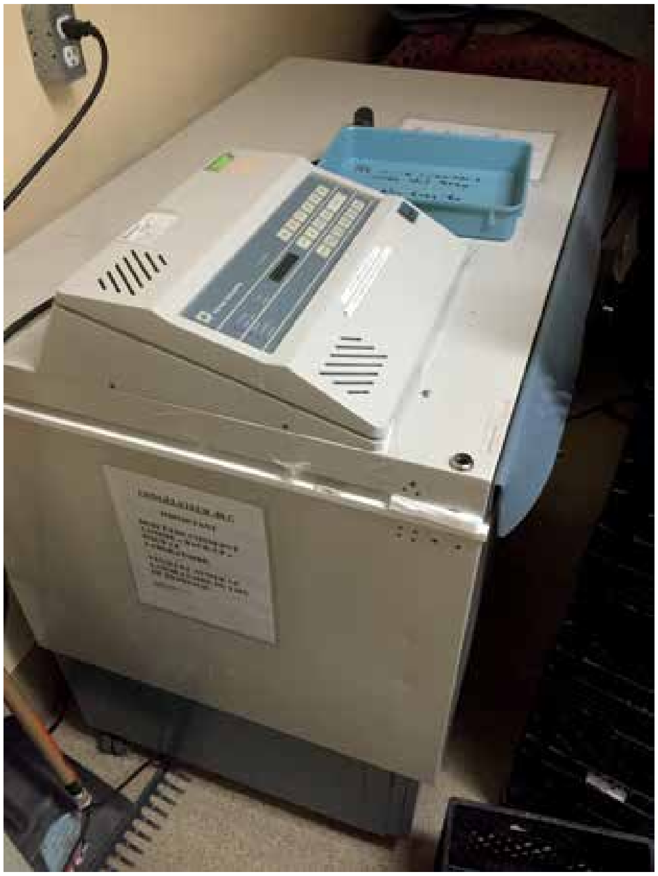

Figure 4. Minus 80 deg C freezer used for this study at the hospital in Kuujjuaq.

- Recruitment, anthropometry, and specimen collection has begun in Kuujjuaq (Figures 5, 6 and 7).

10. Coordinating activities with other network teams

- As advised by ArcticNet, we have worked closely with the Sherilee Harper team to coordinate our activities in Nunavut. In year 2, we made considerable progress toward harmonising the methods to be used for subtyping of protozoans identified in human, animal, and environmental specimens. We have generated a list of candidate loci useful for molecular subtyping proposed by each group (shown in results section) and have agreed on methodologies for multilocus sequence analysis.
- Regular conference calls between teams with the aims of harmonizing CRFs, microbiological methods, and study protocols (Figure 8, 9).
- Coordination of planned activities with the team performing the Nunavik Health Survey 2017 (Team Leader: Pierre Ayotte) regarding investigations of infections.

11. Training of HQP for this project

This project has substantially contributed to training of HQP in years 1-2:

- Koray Demir is a third-year undergraduate medical student (this category is not indicated on the ArcticNet portal, so he is designated as an Honours Undergraduate Student there). Koray won a 2016 Cavazzoni Award for Global Health Research ($5000) and used it to join CY on a preparatory field visit to Kuujjuaq in July 2016. During this trip, he participated in all aspects of the project. Koray presented his work at McGill's Global Health Night in Nov 2016, and remains actively involved in the project.
- Chelsea Caya holds an MSc-PH from McGill University and works as the Research Coordinator for this project. She is intimately involved in all aspects of the project, and aims to acquire experience with fieldwork and publications in order to pursue further graduate work.
- Dr. Asma Iqbal holds a PhD in molecular biology and is a Post-Doctoral Researcher based at McGill University Health Centre - Research Institute. She joined our team in July 2016 after working in Brent Dixon's lab at Health Canada where she gained national recognition as an expert in protozoan genotyping strategies. For our project, she has a specific role in the genotyping of Cryptosporidium and Giardia found during the study. This information will provide unprecedented information on the biology and molecular epidemiology of enteric parasitoses in the Arctic.

Table 1. Candidate loci and primer sequences for subtyping Cryptosporidium spp from individual specimens, to be harmonized across ArcticNet NI working with human, animal, and environmental specimens.

Group & source	Target Locus	Primer	Primer name	Primer sequence	Amplicon length	Ref
Group 1						
	gp60	EF	LX0374	TTACTCTCCGTTATAGTCTCC	925	Xiao et al 2009
		ER	LX0375	GGAAGGAACGATGTATCTGA		
		IF	AL3532	TCCGCTGTATTCTCAGCC	886	Alves et al 2003
		IR	AL3534	GCAGAGGAACCAGCATC		**Peng et al 2001**
Group 2 - Clams						
	M18S	EF	358-F	CGGGTAACGGGGAATTAGGG	751	Shapiro (to be published 2018)
		ER	1141-R	TCAGCCTTGCGACCATACTC		
		IF	153-F	TGGAATGAGTTAAGTATAAACCCCT	543	
		IR	695-R	GCTGAAGGAGTAAGGAACAACC		
	GP60	EF		ATGAGATTGTCGCTCATTATC	980-1000	Iqbal 2012
		ER		TTACAACACGAATAAGGCTGC		
		IF		GCCGTTCCACTCAGAGGAAC	450	
		IR		CCACATTACAAATGAAGTGCCGC		
Group 2 - Water						
	Xiao (18S)	EF		TTCTAGAGCTAATACATGCG		
		ER		CCCATTTCCTTCGAAACAGGA		
		IF		GGAAGGGTTGTATTTATTAGATAAAG	819-825	Xiao 2000
		IR		AAGGAGTAAGGAACAACCTCCA		
Group 3 - Humans						
	18S rRNA		N-DIAGF2	CAATTGGAGGGCAAGTCTGGTGCCAGC	450 bp	Nichols 2003
			N-DIAGR2	CCTTCCTATGTCTGGACCTGGTGAGT		
			CPB-DIAGF	AAGCTCGTAGTTGGATTTCTG		Johnson 1995
			CPB-DIAGR	TAAGGTGCTGAAGGAGTAAGG		
	gp60		gp15-ATG	ATGAGATTGTCGCTCATTATC	~980-1000bp	
			gp15-STOP	TTACAACACGAATAAGGCTGC		
			gp15-15A	GCCGTTCCACTCAGAGGAAC	450bp	
			gp15-15E	CCACATTACAAATGAAGTGCCGC		
	gp60		AL3531	ATAGTCTCCGCTGTATTC	~800bp	Gatei 2007
			AL3535	GGAAGGAACGATGTATCT		
			AL3532	TCCGCTGTATTCTCAGCC		
			AL3534	GCAGAGGAACCAGCATC		

For 2017-2018, several more HQP have joined our team since the submission of the last progress report, including one student from Nunavik:

- Lydia Audlaluk is an Undergraduate Student at Concordia University, and is from Ivujivik in Nunavik. She joined our team as a part-time student researcher in April 2017, and will be responsible for obtaining informed consent from parents in Kuujjuaq and performing monthly questionnaires about diarrhea and food security in households. She will travel to Kuujjuaq in May

Table 2. Candidate loci and primer sequences for subtyping Giardia spp from individual specimens, to be harmonized across ArcticNet NI working with human, animal, and environmental specimens.

Group & source	Target Locus	nPCR	Primer name	Primer Sequence	Amplicon Size	Author
Group 1						
	18S	OF	Gia2029	AAGTGTGGTGCAGACGGACTC	497 bp	Appleby 2003
		OR	Gia2150c	CTGCTGCCGTCCTTGGATGT		
		IF	RH11	CATCCGGTCGATCCTGCC	292 bp	Hopkins 1997
		IR	RH4	AGTCGAACCCTGATTCTCCGCCAGG		Appleby 2003
	TPI	OF	AL3543	AAATIATGCCTGCTCGTCG	603 bp	Sulaiman 2003
		OR	AL3546	CAAACCTTITCCGCAAACC		
		IF	AL3544	CCCTTCATCGGIGGTAACTT	530 bp	
		IR	AL3545	GTGGCCACCACICCCGTGCC		
	gdh	OF	Gdh1	TTCCGTRTYCAGTACAACTC		Caccio et al 2008
		OR	GGdh2	ACCTCGTTCTGRGTGGCGCA		
		IF	Gdh3	ATGACYGAGCTYCAGAGGCACGT	530 bp	
		IR	Gdh4	GTGGCGCARGGCATGATGCA		
	b-giardin	OF	G7	AAGCCCGACGACCTCACCCGCAGTGC	753 bp	Caccio et al 2002
		OR	G759	GAGGCCGCCCTGGATCTTCGAGACGAC		
		IF	F-Lalle	GAACGAGATCGAGGTCCG		Lalle 2005
		IR	R-Lalle	CTCGACGAGCTTCGTGTT		
Group 2 - Clams						
	gdh	EF	GDHeF	TCAACGTYAAYCGYGGYTTCCGT		Reed 2004
		ER	GDHiR	GTTRTCCTTGCACATCTCC		
		IF	GDHiF	CAGTACAACTCYGCTCTCGG	432	
		IR = ER	GDHiR	same as ER		
Group 3 - humans						
	16S		Gia2029	AAGTGTGGTGCAGACGGACTC	497 bp	Applebee 2003
			Gia2150c	CTGCTGCCGTCCTTGGATGT		
			RH11	CATCCGGTCGATCCTGCC	292 bp	Hopkins 1997
			RH4	AGTCGAACCCTGATTCTCCGCCAGG		Applebee 2003
	gdh		GDHeF	TCAACGTYAAYCGYGGYTTCCGT		Reed 2004
			GDHiR	GTTRTCCTTGCACATCTCC		
			GDHiF	CAGTACAACTCYGCTCTCGG	432 bp	
			GDHiR	GTTRTCCTTGCACATCTCC		

2017 and will continue working with the projects throughout the coming year, administering surveys by phone.

- Elizabeth Serra is an MSc-PH candidate at McGill and joined our team in April 2017, for a 14-week public health practicum. She will be travelling to Kuujjuaq and Iqaluit in May-June 2017 to perform primary data collection in both sites.
- Harry Kim is an Honours Undergraduate Student in Microbiology and Immunology at McGill. He

Figure 5. Secured study logbook kept at each study site.

was awarded a 2017 Cavazzoni Award for Global Health Research ($5000) and will use it to join CY on a data collection field visit to Kuujjuaq in August 2016. Throught the summer, Harry will work with the rest of the team to prepare, and will present his work at McGill's Global Health Night in Nov 2017. In addition, Harry's Honours project next year is focused on *Cryptosporidium* and he will work with Dr. Iqbal on the molecular characterization of parasitic pathogens identified during the study.

RESULTS

Recruitment of study participants started in Dec 2016 in Kuujjuaq and is imminent in Iqaluit. Interim analysis of stool specimens, anthropometric data, and questionnaire data are planned for mid 2017 and will be presented at the International Arctic Change 2017 Conference in Dec 2017.

In addition, 2 peer-reviewed manuscripts were published this year on the basis of our group's preliminary data:

- Yansouni CP*, Pernica JM, and Goldfarb D. Enteric Parasites in Arctic Communities: Tip of the Iceberg? Trends Parasitol. 2016; 32(11):834-838. (invited review).
- Thivierge K, Iqbal A, Dixon B, Dion R, Levesque B, Cantin P, Cédilotte L, Ndao M, Proulx J-F, and Yansouni CP*. *Cryptosporidium hominis* is a newly recognized pathogen in the Arctic region Nunavik, Canada: Molecular characterization of an outbreak. PLOS Neglect Trop Dis 2016;10(4):e0004534.

Key results described in Thivierge et al. included the lack of detectable waterborne *Cryptosporidium* oocysts in the index outbreak village, and a first description of the molecular epidemiology of cryptosporidiosis in the region. For stool specimens from 14/51 cases, species and genotypes of *Cryptosporidium* were determined by PCR amplification and sequencing of a portion of the gene encoding the small subunit (SSU) rRNA. Genetic subtyping was determined by DNA sequence analysis of the 60 kDa glycoprotein (gp60) gene. BLAST results of these gp60-positive samples showed that all aligned with *C. hominis* subtype Id. Phylogenetic analysis of the sequence data of gp60 *C. hominis* genotype Id was conducted using the neighbour-joining method. Further analysis demonstrated single isolates of the subtypes IdA13, IdA14G1 IdA14G2R1 and IdA16, and five isolates each of subtypes IdA14 and IdA15. All 14 nucleotide sequences of the gp60 gene of *Cryptosporidium hominis* isolates were deposited in GenBank under accession numbers KU179651 to KU179664 (Figure 3 and Table 3 in the paper). This work was awarded the Dr. Donald A. Henderson Prize for Outstanding Global Health Research 2016; McGill University Global Health Programs.

Finally, NCE funding has allowed our laboratory to recruit a post-doctoral researcher (Dr. Asma Iqbal) and implement enteric protozoan genotyping methods

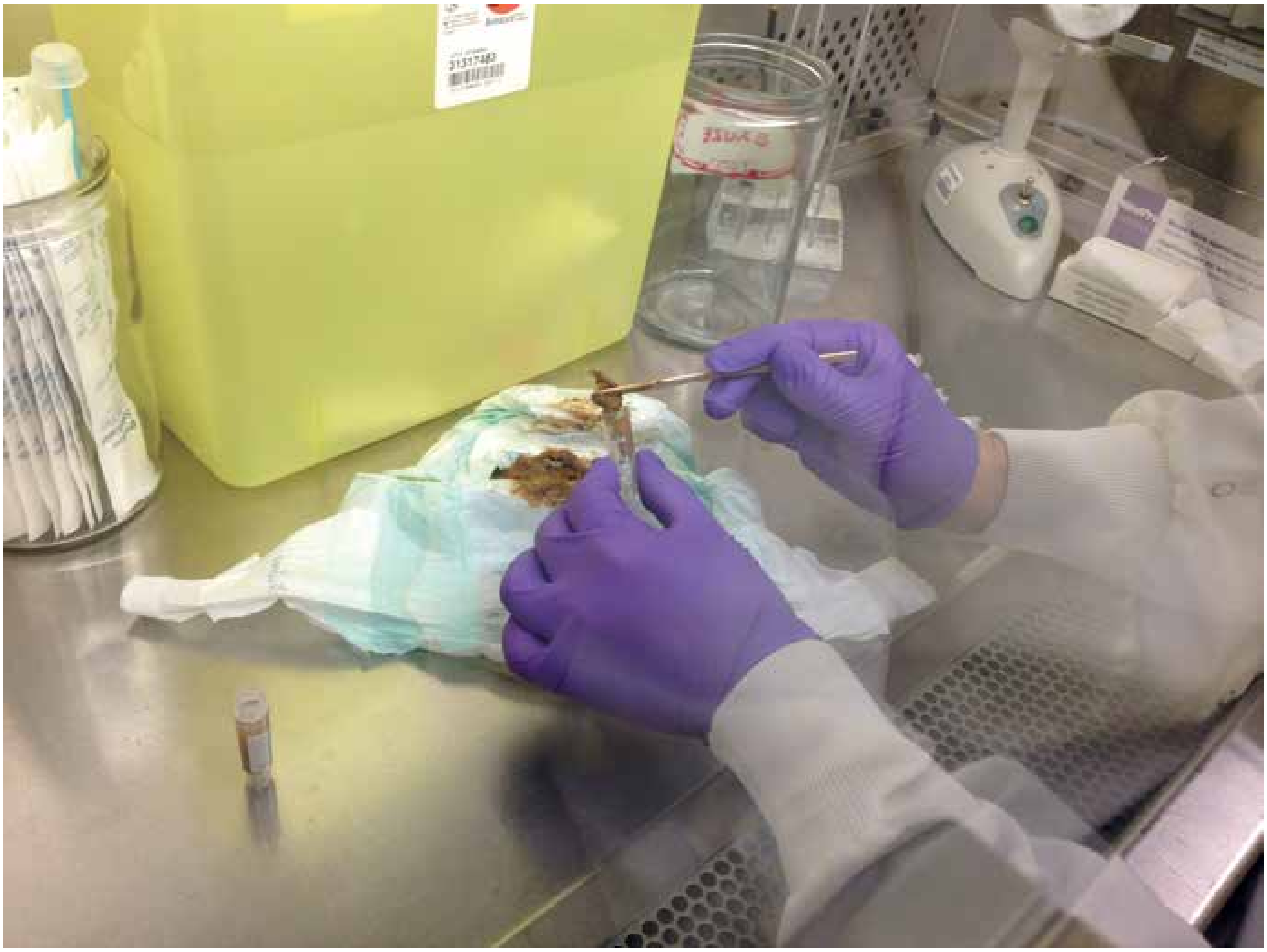

Figure 6. Aliquoting stool specimens from soiled diapers. Using diapers allows the collection of specimens with minimal disruption to participating children, their families, and caregivers.

that will serve as the basis of this and subsequent projects. In year 2, we worked with Dr. Harper's group and made considerable progress toward harmonising the methods to be used for subtyping of protozoans identified in human, animal, and environmental specimens. This will ensure comparability of the results from both groups. We have generated a list of candidate loci useful for molecular subtyping proposed by each group (shown in results section) and have agreed on methodologies for multilocus sequence analysis. The candidate loci for subtyping *Cryptosporidium* and *Giardia* from individual specimens are shown in Table 1 and Table 2.

DISCUSSION

Preliminary data from our group detail the occurrence and high frequency of human cryptosporidiosis in the Arctic, in a region where this disease was not previously known. Growth faltering has been repeatedly found in populations of Inuit children. This likely reflects the fact that several studies in northern Canada report rates of food insecurity among the highest in any high-income country. This suggests that a substantial portion of children living in Arctic communities are at high risk for growth failure, and

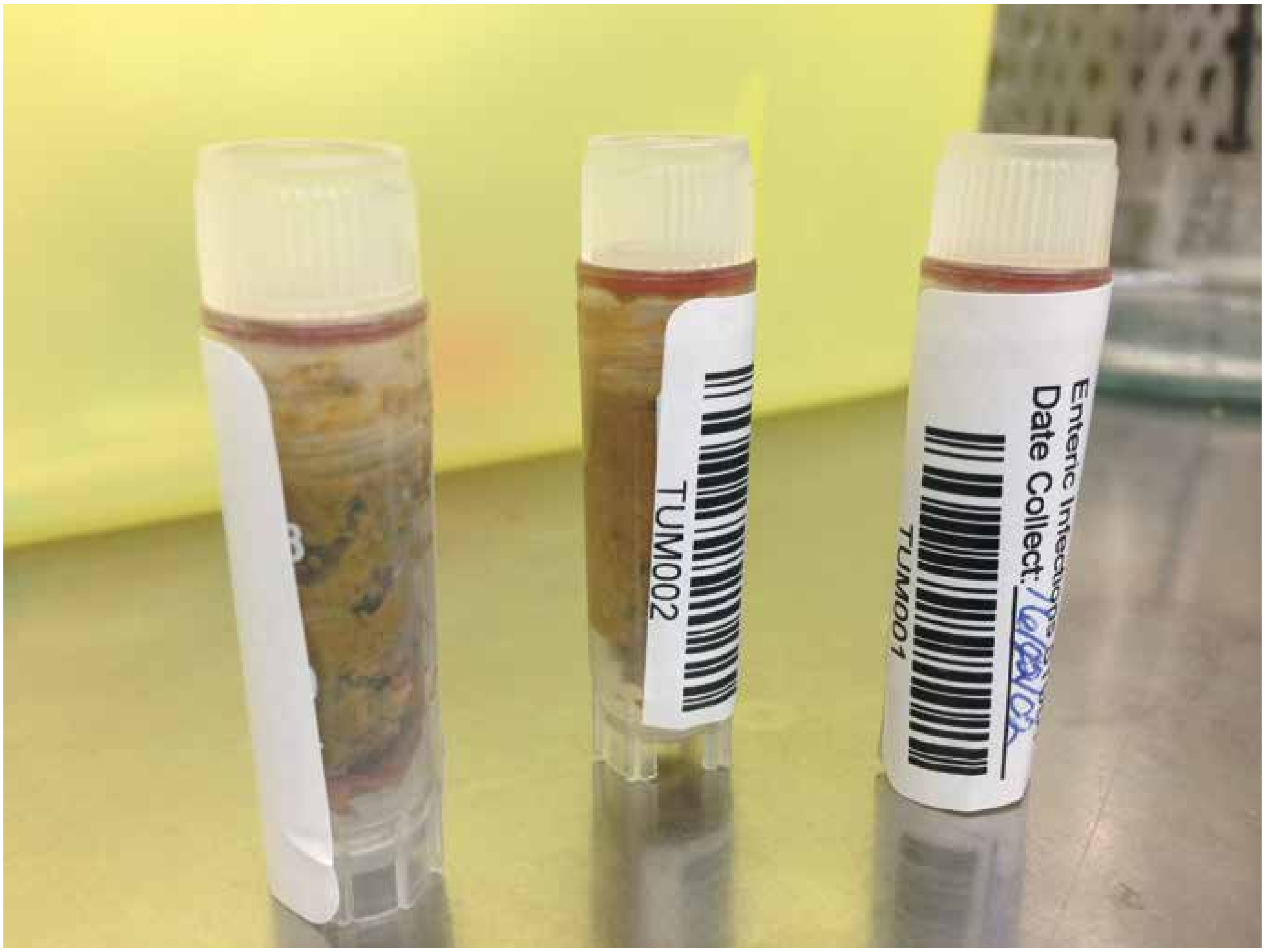

Figure 7. Denominalized stool specimens, identified by a study number and specially-generated barcode that is used across data collection instruments for a given study participant.

that an added burden of repeated or chronic enteric infections may push them 'over the edge' in terms of growth failure, abnormal cognitive development, susceptibility to infections, and lead to reduced adult human capital.

Work thus far has laid the groundwork for patient recruitment to the fist prospective cohort on key enteric infections in the Arctic. Such prospective data from symptomatic and "asymptomatic" young children in communities with high rates of enteric infections and cryptosporidiosis are urgently needed, to define whether this enteric disease burden has an independent negative impact on their developmental trajectory. The interaction between enteric infections and the myriad and frequently overlapping factors known to affect growth and development in Arctic communities (e.g. food insecurity, household crowding, environmental toxin exposure, and specific food practices) must be defined for appropriate prioritisation of public health resources. In addition, the molecular epidemiology of key parasites is incompletely understood. Studies using next generation sequencing or multilocus genotyping approaches are needed to better understand the transmission and possible environmental reservoirs of *Cryptosporidium* and *Giardia*. On the global stage,

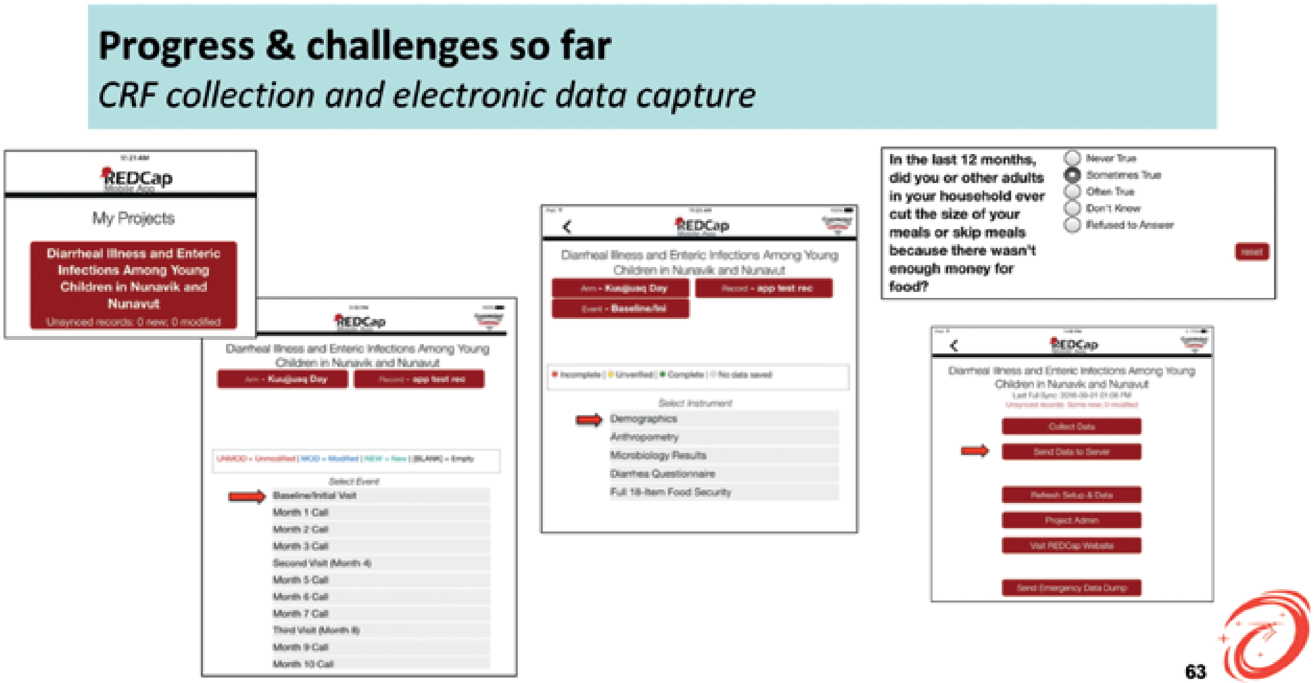

Figure 8. Case report forms and tablet-based electronic data capture using REDCap software.

Figure 9. Overview of stool specimen flow in study sites, from collection to storage, pending shipment to reference laboratories.

several groups and funding agencies have prioritized the development of therapeutics and vaccine targets for *Cryptosporidium* as an urgent unmet need.

Finally, although specific data are the cornerstone of public health policy, their incorporation into participatory community-led prevention strategies, as has been done for trichinellosis, will be required for sustainable policies that consider human practices and environmental changes that disproportionately affect the Arctic.

CONCLUSION

This project now has the financial and logistical requirements to meet the objectives described in the proposal we submitted. Moreover, we have successfully leveraged ArcticNet NCE funds to obtain significant funding from industry partners. In so doing, we have enhanced the relevance and acceptability of these projects to the communities involved by implementing diagnostic services yielding results in a clinically meaningful timeframe during the study. Recruitment has now begun and results will follow in the coming year.

ACKNOWLEDGEMENTS

We sincerely thank our many collaborators in Kuujjuaq, in Iqaluit, members of our team and other Network investigators, colleagues at the Public Health Department of the Nunavik Regional Board of Health and Social Services (NRBHSS); Department of Health, Government of Nunavut; as well as our funders who made this work possible.

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SECTION IV. NORTHERN POLICY AND DEVELOPMENT

Section IV is composed of three ArcticNet research projects discussing national and international policies in relation to the Canadian Arctic socio-economic development in a context of rapid environmental change and modernization.

A "REGIONAL SEAS ARRANGEMENT" FOR THE ARCTIC OCEAN

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ABSTRACT

The Arctic Ocean is almost entirely surrounded by the landmasses of its five coastal states (Canada, Greenland-Denmark, Norway, Russia, and the United States). It is largely a circulating system in which currents, ice, fish, and marine mammals constantly move across national boundaries. Effective management of this system increasingly depends on cooperation among Arctic Ocean coastal states, indigenous peoples, some non-Arctic states and intergovernmental organizations like the EU, and non-state actors such as environmental groups and shipping companies. The UN Convention on the Law of the Sea requires states to cooperate "in formulating and elaborating international rules, standards and recommended practices and procedures … for the protection and preservation of the marine environment, taking into account characteristic regional features." In support of this obligation, the UN Environmental Program (UNEP) has promoted the creation of "regional seas arrangements" (RSAs) to enhance the environmental management of ocean spaces. Today, more than 143 states participate in 14 RSAs established under the auspices of UNEP, and another four RSAs that were established independently. The best-known RSA is the 1992 OSPAR Convention ("Convention for the Protection of the Marine Environment of the North-East Atlantic"), which establishes the OSPAR Commission and brings together 15 states, the European Union, and observers from 27 non-state actors. In September 2014, the US Special Representative for the Arctic, Admiral Robert Papp, announced that the United States was considering promoting an RSA for the Arctic Ocean during its 2015-2017 chairmanship of the Arctic Council. This project explores the potential for an Arctic Ocean RSA. It examines how an agreement could best be designed to: (1) promote and complement the roles of the Arctic Ocean coastal states; (2) promote and complement the role of the Arctic Council; (3) centrally include Arctic indigenous peoples; and (4) take into account the views and interests of other non-state actors. Finally, this project will produce and disseminate a model Arctic Ocean RSA.

KEY MESSAGES

- The Arctic Ocean is a circulating system in which currents, ice, fish, and marine mammals constantly move across national boundaries. It faces numerous management challenges, including jurisdictional uncertainties (extended continental shelves, the Beaufort Sea boundary dispute, the Northwest Passage and Northern Sea Route); shipping; security; search and rescue; oil exploration, development and spills; commercial fishing; biodiversity; land-based pollution; climate change and black carbon.
- The United Nations Convention on the Law of the Sea (UNCLOS) requires states to cooperate "in formulating and elaborating international rules, standards and recommended practices and procedures … for the protection and preservation of the marine environment, taking into account characteristic regional features." There are a number of steps that could be taken under the umbrella of "ecosystem based management", including marine protected areas, bilateral agreements, and regional seas arrangements (RSAs). This project examines these options and the role that Arctic governments, the Arctic Council, indigenous peoples, scientists, shipping companies and other non-state actors can play.
- In the past year, this project has identified, analyzed and mobilized knowledge about two new issues involving potentially serious challenges to the Arctic maritime environment. The first issue concerns Russia's regular use of the North Water Polynya in northern Baffin Bay as a disposal site for rocket stages fueled with highly toxic hydrazine, while the second issue concerns the arrival of large cruise ships in Canadian Arctic waters.

KNOWLEDGE MOBILIZATION

In the past year, the project leader has published a number of op-ed articles based upon research supported by ArcticNet:

- "Why Trudeau should move now to safeguard the Northwest Passage," *Globe and Mail*, 12 August 2016.
- "Arctic cruises: fun for tourists, bad for the environment," *Globe and Mail*, 18 April 2016.
- "Why it's worth it for Canada to talk to the Russian bear," *Globe and Mail*, 19 October 2016.
- "Canada – Russia's Toxic Waste Dump," *National Post*, 20 May 2016.

The project leader was interviewed by CBC Radio ("The Current" & "As It Happens"), CBC TV "The National", Global National, CTV, Radio Canada International, NPR, BBC radio and television. Research and analysis from this project was reported in the Globe and Mail, Toronto Star, National Post, Canadian Press, Associated Press, The Guardian, Washington Post, La Presse, Le Monde, and Neue Zürcher Zeitung.

On 21 July 2016, the project hosted a briefing session in Ottawa on the issue of hydrazine-fueled rocket-stages—for government officials, foreign diplomats, and indigenous and environmental groups. Twenty-five people attended from Global Affairs Canada, Environmental Canada, the Department of National Defence, the Russian, Danish and Norwegian embassies, the Inuit Circumpolar Council, WWF, Greenpeace, and Oceans North. The session shared the project's initial research and analysis of this new issue, so that collaborative, precautionary actions could be taken by decision-makers as quickly as possible.

INTRODUCTION

The Arctic Ocean is a circulating system in which currents, ice, fish, and marine mammals constantly move across national boundaries. Effective management of this system increasingly depends on cooperation among Arctic coastal states, indigenous peoples, some non-Arctic states and intergovernmental organizations like the European Union, and non-state actors such as environmental groups and shipping companies.

The United Nations Convention on the Law of the Sea (UNCLOS) requires states to cooperate "in formulating and elaborating international rules, standards and recommended practices and procedures … for the protection and preservation of the marine environment, taking into account characteristic regional features" (Article 197). There are a number of possible steps that could be taken under the umbrella of what is called "ecosystem based management", including marine protected areas, bilateral accords and regional seas arrangements (RSAs). Around the world, more than 143 states participate in 14 RSAs established under the auspices of United Nations Environmental Program, while another four RSAs were established independently. Bilateral ecosystem based management is also an appropriate response in places like Baffin Bay, where two countries share jurisdiction and therefore responsibility.

This project explores the options for increased international maritime cooperation in the Arctic, including through RSAs and bilateral arrangements. Fifteen papers on different topics of Arctic maritime governance are currently being prepared:

- Extended continental shelves;
- Maritime boundaries and joint management regimes;
- International straits and internal waters;
- Shipping;
- Search and Rescue & Emergency Response;
- Security;
- Seabed Activities;
- Living Marine Resources;
- Biodiversity;

- Land-based Pollution;
- Climate Change and Black Carbon;
- Ecosystem Based Management;
- Arctic Council;
- Indigenous Peoples Cooperation;
- Scientific Cooperation

At the conclusion of the project, we will submit the papers and a model Arctic RSA to a leading university press, in order to maximize the accessibility, influence and "shelf-life" of our research.

At the same time, the project is supporting research, analysis and knowledge mobilization on newly arising issues such as the arrival of large cruise ships in the Canadian Arctic and the use of the North Water Polynya as a disposal location for rocket-stages fueled by highly toxic hydrazine. Additionally, some of the project research has assisted in the preparation of a "knowledge synthesis report" on Arctic offshore oil that was presented to government officials at a key time in Canadian policy-making.

ACTIVITIES

The project is proceeding very well, with some adjustments in response to new developments. Up to this point, we have accomplished the following:

Literature review – The literature on Regional Seas Arrangements (RSAs) and Ecosystem-based Management (EBM) has been collected, examined, and synthesized.

Briefing session in Ottawa – On 21 July 2016, in Ottawa, a briefing session was held on the issue of Russia using the North Water Polynya as a disposal site for hydrazine-fueled rocket stages. Twenty-five people attended, from Global Affairs Canada, Environmental Canada, the Department of National Defence, the Russian, Danish and Norwegian embassies, the Inuit Circumpolar Council, the Government of Nunavut, WWF, Greenpeace, and Oceans North. The session was intended to share the project's initial research and analysis of this new issue so that collaborative, precautionary actions could be taken by decision-makers as soon as possible.

Consultations – A large number of consultations with decision-makers and stakeholders have taken place, including Sheila Watt-Cloutier (former chair of the Inuit Circumpolar Council), Jean Boutet (Senior Arctic adviser to the Canadian Foreign Minister), Jutta Wark (Director, Circumpolar Affairs, Global Affair Canada), Lawrence Cannon (Canadian Ambassador to France and former Canadian Foreign Minister), Alexander Darchiev (Ambassador of the Russian Foreign Ministry), and Rolf Einar Fife (Norwegian Ambassador to France and former Legal Adviser to the Norwegian Foreign Minister).

Publishing – The Network Investigators and Collaborators are all publishing as a result of their work in this project. For example, David VanderZwaag has an article on "Arctic Ocean Governance: Shifting Seascapes, Hazy Horizons" in the Journal of International Cooperation Studies. Michael Byers has a chapter on "The Law and Politics of the Lomonosov Ridge" in Myron Nordquist, Challenges of the Arctic: Continental Shelf, Navigation, and Fisheries (Dordrecht: Brill, 2016). Suzanne Lalonde has a chapter on "Searching for Common Ground in Evolving Canadian and EU Arctic Strategies" forthcoming in N. Liu, ed., *The European Union and the Arctic* (Leiden: Brill, 2017).

Conference attendance – The Network Investigators and Collaborators have spoken at numerous conferences on topics addressed by the project. For example, Susanne Lalonde participated in an "Arctic Marine Cooperation Workshop" organized by the Meridian Institute in Washington, D.C., in May 2016. She also participated in an Arctic Policy Roundtable organized by Global Affairs Canada in June 2016. David VanderZwaag spoke on "Governance of the Arctic Ocean beyond National Jurisdiction: Cooperative Currents, Restless Sea" at the IUCN World Conservation Congress in September 2016, on "International Regulation of Arctic Ocean Fisheries, Shipping and Tourism: Cooperative Currents, Sea of Challenges" at the 2016 North Pacific Arctic Conference in August 2016, and on "Governance of the Arctic Ocean beyond National Jurisdiction: Cooperative Currents, Restless Sea" at the Fourth Sino-Canadian Exchange on the Arctic in May 2016. In November 2016, Michael Byers spoke at a conference on Russia-Canada Arctic cooperation in Ottawa. In December 2016, he spoken on the opening plenary panel of the ArcticNet ASM. Michael Byers also attended an "Arctic summit" on the CCGS *Amundsen* in September 2016, sharing his research with senior officials, foreign ambassadors, and industry leaders.

We are currently in the following stages of the project:

Project workshop – The workshop has been postponed until 13 & 14 May 2017. For this reason, some carry-over of funds into the next financial year will be required.

Book proposal – Following the project workshop, a book proposal will be developed and submitted to a leading university press. At the same time, the draft papers will be revised, augmented and refined in light of input received.

Draft model Arctic Ocean RSA – The draft papers and workshop discussion will be used as a basis for the first draft of a model Arctic Ocean RSA. This draft will be circulated for comment to the entire project team, as well as to Northern governments, Arctic indigenous peoples, Arctic Council committees and task forces, environmental groups, companies and industry associations.

International conference – In early 2018, the final drafts of the papers and the model Arctic Ocean RSA will provide a focus for an international conference that brings the project team together with different stakeholders (Arctic governments, Arctic indigenous peoples, environmental groups, companies and industry associations) as well as other international experts and the media.

RESULTS

Although this project is in only its middle stage, we have developed a comprehensive view of the existing literature, published a number of initial papers, and adjusted our overall plan to engage in research, analysis and knowledge mobilization with regard to current developments.

In the past year, two new and potentially very important issues arose within the scope of our research: the arrival of large cruise ships in the Canadian Arctic; and the discovery that Russia is regularly using the North Water Polynya in northern Baffin Bay as a disposal site for rocket-stages fueled by highly toxic hydrazine. The project team used the research and expertise developed with ArcticNet support to engage directly and publicly with these issues, contributing to some positive results.

In the case of the former issue, Transport Canada is now working with Arctic cruise ship operators and communities on a code of conduct that will address many of the concerns the project team identified, analyzed and brought to the attention of media and government.

In the case of the latter issue, in June 2016 the Russian government announced that it will phase out the use of hydrazine-fueled rockets for launches into polar orbit. This announcement came less than one week after the project team drew international media attention to the issue.

DISCUSSION

By August 2015, it had become clear that the United States was pulling back from its plan to negotiate a full Arctic Ocean Regional Seas Arrangement during its 2015-2017 chairmanship of the Arctic Council. The US instead advanced a looser set of initiatives under the umbrella of “ecosystem based management”. According to David Balton, then the US Chair of the Arctic Council, this looser set of initiatives might at some later date be gathered together into an Arctic Ocean RSA.

In September 2015, the three Network Investigators decided that our project needed to take a more comprehensive approach than initially planned, in order to develop a knowledge base that is broad and deep enough for us to draft a model Arctic Ocean RSA in the absence of a parallel, official, US-led process. For this reason, fifteen papers on specific topics of Arctic governance are being researched and written. These papers will be workshopped in May 2017. We will then develop and refine the papers for publication and also, concurrently, begin the process of drafting and consulting on a model Arctic Ocean RSA.

In the past year, the most interesting aspects of this project concerned two new issues that arose within the scope of our research: the arrival of large cruise ships in the Canadian Arctic; and our discovery that Russia regularly uses the North Water Polynya as a disposal site for rocket stages fueled by highly toxic hydrazine. As these issues emerged, the project team was able to respond rapidly with research, analysis and knowledge synthesis that engaged and informed government officials, foreign diplomats, indigenous and environmental groups, and the global media.

On the former issue, Transport Canada is now working with Arctic cruise ship operators and communities on a code of conduct that will address many of the concerns we identified. On the latter issue, the Russian government has announced that it will phase out the use of hydrazine-fueled rockets for launches into polar orbit. This announcement came just one week after the project team turned the issue of the rockets, and their potential impact on the North Water Polynya, into an international news story.

CONCLUSION

The project is making excellent progress despite several necessary adjustments resulting from: (1) A change in the US approach to the issue of Arctic Ocean governance during its 2015-2017 chairmanship of the Arctic Council; (2) The arrival of large cruise ships in the Canadian Arctic; and (3) The discovery, as a result of research being conducted by this project, that Russia regularly uses an ecologically important area within Canada’s Arctic waters as a disposal site for rocket stages fueled by highly toxic hydrazine.

We have conducted an extensive literature review, identified fifteen key issues, and are workshopping papers in May 2017. We plan to publish revised versions of the papers with a leading university press. We also plan to draft a model Arctic Ocean regional seas arrangement (RSA) that can assist Arctic governments as they work towards an eventual, actual RSA. Finally, we will continue to work on the issues of large cruise ships and hydrazine-fueled rockets, and to inform and advise government officials, indigenous and environmental groups, and industry stakeholders.

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SUPPORTING UNDERSTANDING, POLICY AND ACTION FOR FOOD SECURITY IN NUNAVIK AND NUNATSIAVUT

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Community freezers in Nunatsiavut: benefits and risks for sustainable food security in Inuit communities
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ABSTRACT

Food insecurity is a critical public health issue in many northern communities today. Various forms of environmental, socio-cultural, economic and political change threaten northern households' abilities to access and acquire adequate, healthy, safe and preferred foods on a regular basis. Action is needed to address this issue but must be based on accurate and relevant information gathered at the appropriate scale. This project is being conducted in cooperation with the Nunavik Regional Board of Health and Social Services and the Nunatsiavut Government to support Nunavik and Nunatsiavut residents, and community and regional organizations in understanding and taking action on food insecurity at the community and regional scales. The project involves household food security surveys in Nunavik, analysis of existing datasets in the two regions to determine the role of various factors, including existing food support programs, in household food security status, and a policy and program review and knowledge translation activities to support decision making and policy discussions in the two regions to address long term food security challenges.

KEY MESSAGES

- Despite growing recognition and dialogue among researchers on the gaps and limitations in current food security literature, a proliferation of literature using similar approaches continues.
- While no currently existing food security assessment tool adequately evaluates all domains of the concept in Inuit communities, the Household Food Insecurity Access Scale appears to address the largest number of priorities applicable to the Inuit food context.
- While it performs relatively well, the Household Food Insecurity Access Scale does not adequately identify individuals who are relatively food secure or very food insecure (e.g. hungry).
- As hypothesized, but not yet shown in existing datasets, level of participation in hunting and fishing activity appears to have a significant effect on Inuit household food security status.
- As hypothesized, but not yet shown in existing datasets, different factors influence food insecurity status among different segments of the Inuit population (e.g. young women and middle-aged men are more food insecure than other groups in Nunavik).
- Results from household food security surveys in Nunatsiavut indicate that the community may be a critical scale at which to understand this issue as represented by significant variation in prevalence between communities in the same region.
- Ability to meet 'food needs' is a missing component from food security analysis and varies between individuals and households within communities and across communities in the same region.

OBJECTIVES

We continued to pursue the objectives identified in 2015, at the start of our ArcticNet phase III project:

1. Increase understanding at the household and community scales of status and determinants of food insecurity in the two regions and the role of specific food support programs;
2. Adapt and validate a food security assessment tool for use in Inuit communities and apply it in a pilot trial in Nunatsiavut and through the Qanuippitaa survey in Nunavik; and
3. Conduct policy and program review and knowledge translation activities to support decision making and policy discussions in the two regions to address long term food security challenges.

KNOWLEDGE MOBILIZATION

- Convened knowledge translation and mobilization meeting in Nunatsiavut (March 2017) with government representatives to understand and plan action in association with the return of results from this project.
- Team member, K McTavish, hired as Nunatsiavut regional food security coordinator responsible for leading activities and strategies to address food security in the region. Resulting, ongoing meetings with Nunatsiavut Government (weekly meetings) on knowledge mobilization planning.
- Submitted two proposals, two more planned, to continue and expand on work started under this project to continue dataset and develop intervention activities.
- Travelled (March 2017) to all (five) Nunatsiavut communities and Happy-Valley Goose Bay to present results (community meeting, open house, distribution of print material and regional report, presentations to key groups and committees) on food security and food needs assessment surveys.
- Attended Nunatsiavut Regional Food Security Summit and presented to Baker Lake Niqitsiavut Committee and held open house in Baker Lake on community food security survey results.
- Met with representatives of Nunavik Regional Board of Health and Social Services and Nunavik Food Security Working Group to present update on food security policy landscape review and analysis.
- Hosted Baker Lake community food security coordinator and co-presented on that community's food assessment process at National Indigenous Health Conference.
- Completed three published and three submitted manuscripts in international peer reviewed journals.
- Presented 15 oral and 4 poster presentations at national and international scientific conferences.

INTRODUCTION

The Canadian Council of Academies expert panel assessment on Aboriginal food security in northern Canada concluded "that there is a food crisis in northern Canada. This crisis, which is more evident in Aboriginal populations, has long-term implications for the health and well-being of these communities" (CCA, 2014: 193). Various forms of environmental, socio-cultural, economic and political change all threaten northern households' abilities to access and acquire adequate, healthy, safe and preferred foods on a regular basis. Sixty-two percent of Inuit households in Canada are considered to be food insecure (Huet et al., 2012). At the regional level, these rates range from 24% in Nunavik (note: not a comparable statistic to the USDA HFSSM generated level reported for other Inuit regions) to nearly 70% in Nunavut (Rosol et al., 2012). Inuit communities face increasing challenges of accessing adequate nutrition including high costs and limited availability of healthy foods, increasing cost of hunting and harvesting traditional food, limited employment opportunities and low household incomes, changing dietary habits, limited awareness of healthy eating habits, and various forms of environmental change (climate change and variability, presence of environmental contaminants etc) (Krummel, 2009, Lambden et al., 2006; CCA, 2014; Organ et al., 2014). These challenges have been associated with a nutrition transition in many Inuit communities where growing consumption of low-nutrient- store-bought foods and decreasing consumption of traditional foods are contributing to the increasing prevalence of diet-related health problems, such as obesity, diabetes, and cardiovascular disease amongst populations that have traditionally experienced low levels of such conditions (Mead et al., 2010, Egeland et al., 2009). Individuals who are food insecure have significantly higher odds of being overweight, having poorer nutritional status, are at greater risk for many chronic diseases, have poorer functional health and experience slower growth (Willows et al., 2011, Pirkle et al., 2014). The CCA expert panel was warranted in calling this a crisis situation, and one needing immediate action. However, action must be based on robust information focused at the appropriate scale, considerate of the most relevant factors and aware of the fact that it often requires the coordinated engagement of a diversity of partners to have sustained impact on this topic (Wakegejig et al., 2013).

Despite recognition of the importance of the issue of food insecurity in Inuit communities there are still significant challenges to providing decision makers at the household, community or regional level with the needed information upon which to take informed action. Issues of reliability, validity and spatial and temporal comparability of food security rates exist because of a lack of previous validation of the widely, but inconsistently used USDA Household Food Security Survey Module in many Inuit communities (CCA, 2014). A lack of examination of scale in previous and current data collection efforts has minimized our understanding of the importance of such things as sharing networks in food security status in Inuit communities. Finally, despite the growing number of interventions/programs developed and implemented to address this issue few initiatives have been evaluated in regards to their impacts on household food security status, and individual food behaviours (CCA, 2014).

In cooperation with the Nunavik Regional Board of Health and Social Services, the Nunatsiavut Government, and the Niqitsiavut Committee in Baker Lake, NU this project is working to support Inuit residents, and community and regional organizations to understand and take action on food insecurity at the community and regional scales.

ACTIVITIES & RESULTS

We have been conducting activities in 2016-17 to meet the objectives of the research program as initially developed in 2015. Specific research activities, their association with overall program objectives, and findings to date are presented below.

Activity 1: Review and Analysis of Circumpolar Food Security Literature (Activity leads: Furgal, Rajdev)

Objectives: 1, 2, 3

While food security in the circumpolar region has been identified as a critical issue affecting many Arctic communities very little is known of what trends and patterns exist in the literature discussing the issue. The objective of this project was to identify the trends, patterns, strengths and gaps in the study of food security in peer-reviewed and grey literature in the circumpolar region by conducting a systematic literature review. This year we updated and completed our collection and analysis of this literature on aspects of food security (food availability, food accessibility, food quality and food utilization) in the circumpolar region spanning the years 1953 to 2016.

Results

Both the peer reviewed and grey literature show continuous growth in food security-focused research communication in the circumpolar region. With the 2016 data included, the same patterns in the literature appear to exist: a larger proportion of the publications relate to the Inuit population than any other; the majority of the literature focuses on Arctic Canada; the majority of sources speak to issues of food quality, followed by accessibility, availability and then utilization. The trends in research publications reflect a continuous research focus on the topic and increased interest in the nutrient and chemical, and cultural qualities of food, and social and economic accessibility of food. Greater attention needs to focus on food availability (political and physical accessibility), food quality (biological) and utilization (knowledge and skills).

Activities 2, 3: Nunavik regional ranking and prioritization for food security tool adaptation and Review and evaluation of existing food security tools and their applicability for the Inuit food context (Activity leads: Furgal, Lucas, Pirkle, Willson)

Objectives: 1, 2, 3

One of the goals of this project is to work with regional decision makers to identify limitations in current food security assessment data and tools, and identify priorities and needs for tool adaptation, development and use. After analysis of last year's consultation and ranking survey with regional representatives, it was recommended to identify the HFIAS as the most likely tool for future use in the two regions to assess household food security status. Meanwhile, the review of existing food security assessment tools presented in the literature identified the Household Food Security Survey Module (HFSSM) as the best, albeit challenged, tool to assess this issue in Inuit communities. This year, further consultation with the Nunavik Nutrition and Health Committee (NNHC) in regards to their interests and needs in relation to the data to be gathered under the Qanuilirpitaa 2017 regional Inuit health survey, via its food security questions took place. The need for comparability with other Inuit regional and national datasets was stressed more strongly than before. Further, consideration of the current survey design and sampling strategy for that survey had not been taken into consideration so this was done as well.

Results

We are currently preparing a manuscript on this regional decision maker ranking exercise and its concordance with the analysis of existing assessment tools. Further review and revision of the food security tool questions to be included in the regional health survey took place, taking into consideration the results of the pilot testing of that tool and these new emphases expressed by regional decision makers. As a result, a modified version of the HFSSM (USDA Household Food Security Survey Module) was identified and proposed as the tool to use in future data collection in that region. While all priorities that influence the previous ranking of tools are still important, some of the practical factors such as the overall survey sampling strategy (individual focused) and total sample size to be recruited in the regional Inuit health survey, had a greater bearing on the final decision and recommendation for which questions to use. This modified tool will be used in the regional health survey this fall. The traditional HFSSM will be used in Nunatsiavut communities to repeat data collection on those communities to compare with results from 2014 and look at food security at the community scale and changes over time.

Activity 4: Psychometric validation of the Household Food Insecurity Access Scale among Inuit women from Northern Quebec (Activity leads: Pirkle, Teh, Lucas, Furgal)

Objectives: 2, 3

As part of the Arctic Char Distribution Program designed to help address contaminant exposure and food insecurity among pregnant women in Nunavik, a modified Household Food Insecurity Access Scale (HFIAS) was administered to 131 pregnant women and blood samples were taken to measure nutritional biomarker concentration. We partnered with the researchers involved in that intervention and conducted analysis of the food security tool used and its performance in reporting food insecurity among the participants in support of Objectives 2 and 3 of this study. Data were fit to a Rasch Rating Scale Model (RSM) to determine HFIAS discrimination ability. Several other models were constructed and tested against the original model using Akaiki Information Criterion (AIC) and Bayesian Information Criterion (BIC), which indicate relative information loss with each model. An exploratory factor analysis (EFA) was conducted on the items that the RSM indicated provided the most information. Receiver Operating Characteristic (ROC) curves were used to assess the level of food insecurity associated with clinically low levels of iron depletion biomarkers.

Results

The manuscript was completed this year and submitted for publication and is now being revised for resubmission to PLoS ONE. This work was also presented to the Nunavik Regional Board of Health and Social Services and the Nunavik Nutrition and Health Committee in 2016 as well. One conference presentation was provided on this work in December 2016 at the Annual EcoHealth Conference in Australia.

Activity 5: Qualitative conceptualization and adaptation of Inuit food security assessment tool (Activity leads: Furgal, Willson, McTavish)

Objective: 2

As part of this project and the Community-led Food Assessment project funded through the Public Health Agency of Canada and being led by the Food First NL, we have been developing a process to gather qualitative information in Nunatsiavut to explore the notion of food security or insecurity from a regional perspective. Many of the tools that are currently in use in the Canadian North to assess household food security are critiqued for not being culturally appropriate, or not using terminology or words applicable to local food contexts in these regions. In addition to work on evaluation and validation of currently used tools and their abilities to identify household food insecurity and its associations with critical health outcomes (see reporting on other Activities in this report), we are conducting focus groups with a stratified cross section of community populations in three Nunatsiavut communities this spring/summer. This work was delayed this year, awaiting first the return of results from the community food security assessment surveys in those communities. This work will now proceed later this spring and into the early summer. This qualitative data will be used to identify missing elements of the notion of food insecurity in this, and perhaps other, regions that may not be included in current assessment tools. As well, these focus groups will help us determine the appropriate words, phrases, or terminology to use in food security assessment tools and further adapt existing tools for future use. While waiting to do focus groups in communities we have done a document and literature search on this topic to identify modifications to make to the current food security assessment tools. A presentation containing some of this content was made at the ArcticNet annual scientific meeting this year.

Results

In the Nunavik food security survey tool to be used in the regional Inuit health survey in 2017, we have used wording to be more inclusive to a variety of different ways of accessing food beyond economic purchase. We have used the wording "resources or ways you get food" with an explanation of our meaning at the beginning of the research tool for this survey. Qualitative validation of this wording and approach will further inform its applicability for other regions this year.

Activity 6: Ongoing Analysis of Community level food security status and self-reported food needs data in Nunatsiavut and Baker Lake, Nunavut (Activity leads: Furgal, McTavish, Martin, Willson)

Objectives: 1, 3

In 2014 we conducted household food security surveys with a representative sample of households in 4 of 5 coastal Nunatsiavut communities. We accessed data for the 5th community from the Inuit Health Adaptation to Climate Change Project (IHACC) led by Dr. James Ford and Dr. Sheri Harper. In 2015 we conducted a similar survey among a community representative sample of households in Baker Lake, Nunavut. These surveys included gathering data on self-reported ability to meet food needs and the current use of various existing food support programs. Analysis on these databases has been conducted and is ongoing. We have discussed the results with Nunatsiavut regional representatives, are planning a knowledge translation meeting with them in March 2017 and are discussing with them a communication strategy for the release of this data shortly after. In May 2016 we presented community results to the Baker Lake food security assessment committee. We also held an open house in that community to return results. We are now finalizing communication materials for the two data sets (Nunatsiavut, Baker Lake) for the final results communication this spring.

Results

Results show that food security prevalence levels vary significantly between communities within the same region, and that some of the communities we have surveyed are recording the highest prevalence of food insecurity in Inuit communities to date. Our data on self reported ability to meet food needs is the first data of its kind in Inuit communities. It shows that the ability to meet food needs varies among individuals and households in the same community, and among communities in the same region.

Activity 7: Examination of determinants of food security status in Nunavik through Bayesian modeling (Activity leads: Juillet, Furgal)

Objectives: 1, 2, 3

In Nunavik, a previous analysis we conducted on the "Qanuippitaa? How Are We? 2004" public health survey dataset reported community food insecurity levels ranged from 9% to 51%, while the overall regional rate was 24% (as measured by one question asking about a lack of food in the month prior to the survey). Despite these results, little was revealed about the determinants of food insecurity in the region and their relative importance. Based upon data from the same household questionnaire, in conjunction with the individual questionnaire of the Qanuippitaa? How Are We? 2004 survey, the present study investigated the relative importance of determinants of reported household lack of food in Nunavik using generalized linear mixed models and model selection, based upon information criteria, while accounting for redundancy in explanatory variables.

Results

Our analyses provide strong evidence for a negative relationship between a reported household lack of food in the month prior to the survey and a synthetic index positively associated with seasonal harvesting frequencies reported by the household respondent. In other words, harvesting of country foods is associated with food security status in anyway at communities as was hypothesized but not previously explored in empirical data sets. A manuscript is in preparation to publish this work in the scientific literature.

Activity 8: Towards a multivariate understanding food security determinants and outcomes in Nunavik (Activity leads: Fillion, Furgal, Lucas)

Objectives: 1, 2, 3

Food security is a complex and multidimensional phenomenon which can be influenced by a number of factors and which can be related to health in a number of ways. In order to understand the determinants of food security in Nunavik, we revisited the Qanuippitaa 2004 data to explore the different profiles of food security experiences among participants with the understanding that the determinants of food security may differ throughout the population. Men and women, of different age and in different situations, are likely to have different experiences of food security/insecurity. Understanding how the determinants of food security interact to create different food security profiles in the population will inform interventions for specific target groups and areas in this population and ultimately contribute to the development of a food security assessment tool that is more comprehensive and able to capture these differences that likely exist throughout the region and among sub-populations in Nunavik.

Among the Qanuippitaa 2004 variables documented, we selected those most likely to be environmental and social determinants of food security status as well as being associated with health and nutritional outcomes. Multivariate analysis was completed on this data this year and a manuscript is in preparation for submission to the scientific literature this spring. Results were presented to the Nunavik Nutrition and Health Committee and via a presentation at the Annual ArcticNet Scientific Meeting in December 2016.

Results

Results further support the hypothesis that harvesting of country foods influences individual food security status.

Those less food insecure (cluster 2, Figure 1) in Nunavik included those that harvested more often, had a higher consumption of country foods, and a better economic status. Individuals in this group were mostly men. Those with higher food insecurity (cluster 3, Figure 1) included those that harvested and consumed less country food, and were in a more precarious economic situation. Most individuals in this group were younger women (Fillion et al., 2016 ArcticNet presentation).

Activity 9: Assessment of implementation fidelity of the Arctic Char Distribution Program in Nunavik (Activity leads: Pirkle, Gautier, Lucas, Furgal)

Objectives: 1, 3

When reviewing the circumpolar food security literature we notice few reports of intervention evaluation. Without the documentation of intervention development, implementation and evaluation it is difficult to know what actions are having any effect on household food security status over time. As a result, it is challenging to influence policy change in positive directions in support of positive food support action. In September 2011, the Nunavik Regional Board of Health and Social Services began the Arctic Char Distribution Program (AC-DP) for Pregnant Women. This program promotes the consumption of the fish Arctic Char – a traditional Inuit food that is nutritionally rich and relatively low in contaminants – by pregnant women living in villages of Nunavik, an area in Northern Quebec (Canada) inhabited predominantly by people of Inuit ethnicity. This intervention intends to reduce exposure to contaminants and improve food security in Inuit communities, both of which are important public health issues in the region. However, implementation of the program has been incomplete as it has not covered all intended geographic areas, and its environmental and financial sustainability are challenged. In the interest of learning about the implementation and effectiveness of a food security related program in an Inuit community we assessed the program's implementation based on data collected from program documentation, meeting minutes, field notes, and qualitative interviews with program recipients and implementers and with the results modified an implementation framework initially developed by Carroll et al. (2007) (Gautier et al., 2016). The results of this implementation representing and reviewing the operation of this initiative (Figure 2) have now been communicated back to the Nunavik Regional Board of Health and Social Services and Nunavik Nutrition and Health Committee and a publication has been finalized, revised, accepted and is now in print (Gautier et al., 2016).

Activity 10: Review of Nunavik regional policy landscape and food security priorities (Activity leads: Furgal, Thackeray)

Objective: 3

To explore the question as to whether challenges in the food security policy landscape influence household food security status, a review and analysis of the policies (legislation, statutes, programs, mandates, identified priorities) pertaining to household food security in Nunavik is being conducted. A collection and review of all documents available through online sources pertaining to the elements of food security in Nunavik at the federal, provincial and regional scales has been completed. The initial review was shared with representatives of the Nunavik Regional Board of Health and Social Services and the Nunavik Regional Food Security Working Group. Feedback from that group has provided further focus to this review and analysis and identified the next step in this research process. Results of the policy analysis will be presented to the regional working group in May 2017 at which time focus group discussions will take place with members of this group to discuss ways in which to enhance access to country foods to help address food insecurity in Nunavik.

Results

A total of 398 documents and sources were identified, gathered and reviewed. Just more than 100 were retained for analysis. Each document was reviewed and coded to the four pillars of food security (availability, accessibility, quality, utilization) and several sub-pillars. Feedback from the regional partners has further focused this review and analysis at the provincial and federal levels. A poster on this project was presented at the ArcticNet annual scientific meeting in December 2016.

DISCUSSION

Despite the attention given to the issue of food insecurity in the Canadian Arctic today, as a result of the widespread challenges that exist and their implications for public health, significant gaps remain in our understanding of the topic. This challenges clear and effective action in the form of targeted interventions or appropriate policy responses.

A number of challenges and limitations exist in our interpretation of food security prevalence levels currently reported for the Canadian North. This is the result of a lack of previous validation of the widely, but inconsistently used USDA Household Food Security Survey Module in many Inuit communities (CCA, 2014). Our collection and review of existing tools indicates that while the HFIAS appears to address the largest number of priority areas applicable to the Inuit food context, the HFSSM is more easily comparable because of its common past use. Further, psychometric validation of the HFIAS tool indicates that it performs relatively well yet does not do as good a job at identifying individuals who are relatively food secure or very food insecure (e.g. hungry). This problem may be addressed though by replacing some questions on the HFIAS questionnaire with some questions about access to country foods.

Our research shows the role of country food harvesting and consumption for food security in the validation of the HFIAS as well as the further analysis conducted on the 2004 Qanuippitaa dataset from Nunavik. Surprisingly, this is the first time data has been available to explore this relationship in the same dataset. Results from our food security assessment surveys in Nunatsiavut communities and Baker Lake, Nunavut, show significant differences in the levels of food insecurity from community to community, even within the same region. These and other data gathered support for the argument that local factors require attention when understanding the status of food security at the household level. This argues for more community level exploration and data collection as it appears as though food security could be, in large part, a 'community' phenomenon. The previous lack of examination of scale in previous research on the topic and reliance on territorial or regional scale data has potentially minimized our understanding of the importance of such things as sharing networks, or individual household participation in hunting and fishing activities for food security status.

While there is a growing number of interventions developed and implemented to address Inuit food insecurity few have been evaluated, particularly in terms of their impact on household food security status, and individual food behaviours (CPC, 2014; CCA, 2014). Our research shows that in addition to exploring intervention impact we must also consider

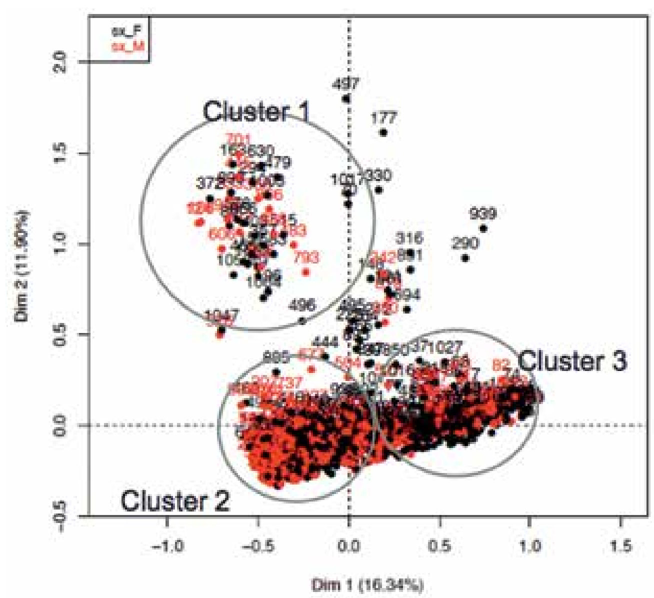

Figure 1. Cluster analysis of individual food security status in Nunavik along two synthetic axes created through MCA. Males are shown in red; females are shown in black.

implementation evaluation to determine the extent to which an intervention functioned as intended. Finally, we are learning more about the complex food security policy landscape relevant for northern regions such as Nunavik and the potential strengths and weaknesses present in that landscape and its potential influence on household food security status.

CONCLUSIONS

This project is addressing identified gaps in understanding of Inuit household food security status through examination of the literature, application of different statistical approaches to the analysis of existing datasets, evaluation of food security interventions and the tools used to do so when possible, the collection of Inuit perspectives and explanations of what it is and what it means to be challenged in accessing food on a regular basis (food insecure) and a review of and consultation with Inuit regional decision makers and those engaged in policy on the topic. Our learning to date has informed responses to a number of questions on the topic. The focus of our research activities is proving very valuable in yielding needed data on certain aspects of the issue (e.g. scale of focus, determinants of food insecurity, tool validity and effectiveness, intervention impact) to support community and regional decision making and action.

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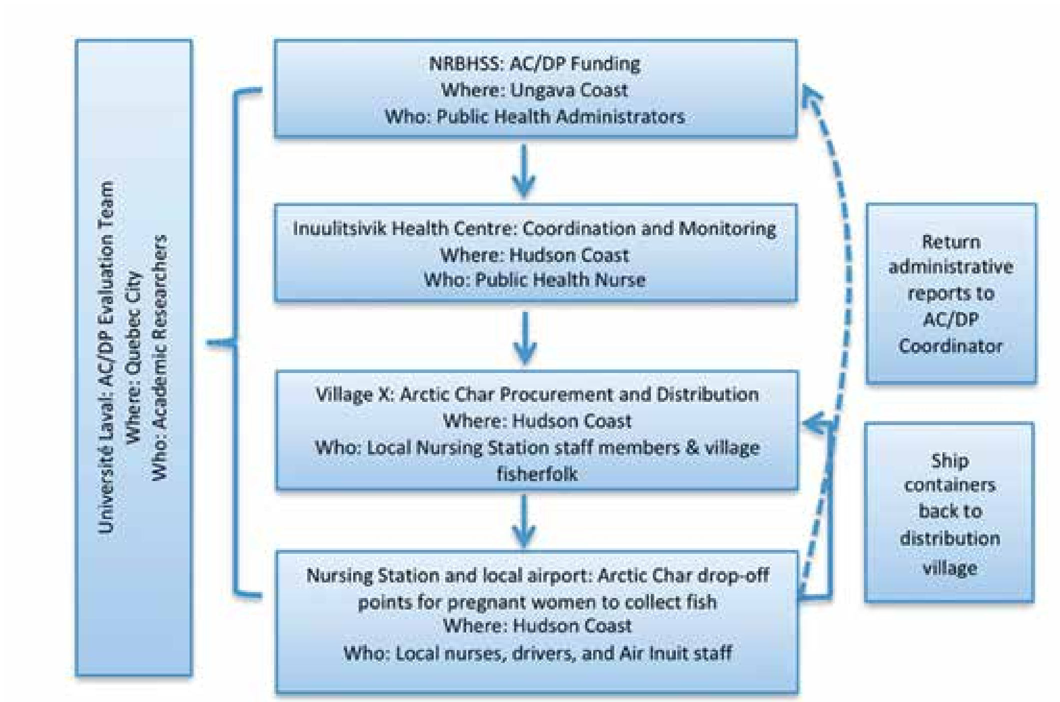

Figure 2. Organization of the Arctic Char Distribution Project (AC/DP). NRBHSS, Nunavik Regional Board of Health and Social Services, Source: project documentation (from Gautier et al., 2016). © 2016 Gautier, Pirkle, Furgal, Lucas.

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MINING ECONOMIES, MINING FAMILIES: EXTRACTIVE INDUSTRIES AND HUMAN DEVELOPMENT IN THE EASTERN SUBARCTIC

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ABSTRACT

Our research project will provide a comprehensive comparative review and assessment of the economic and human development impacts of major extractive industries in the Eastern Subarctic region. The main goal of the project is to establish a mining economic impact evaluation method, adapted to the North, that serves to appraise the local economic benefits resulting from the operating mines in Nunatsiavut and Nunavik. We will document, examine and interpret the experience of Québec-Labrador Inuit workers and entrepreneurs in relation to economic development and the regions' mining sectors. We will conduct surveys to assess the economic links and revenue flows between the Voisey's Bay and Raglan mines and local households and businesses. We will investigate the dynamics between the land-based and mining-based economies in Nunatsiavut and Nunavik by analyzing households spending and employment behaviour. Based on our analysis, we wish to contribute to the development of sustainable mining policies for the Eastern Subarctic and for the Canadian North more generally. The proposed research will address gaps in follow-up studies of large-scale mining activities, highlighting lessons from the experience of mineral developments in Nunatsiavut and Nunavik, and serving to construct an up-to-date, rigorous baseline that is indispensable for assessing, managing, and promoting the participation of Inuit jurisdictions in future extractive projects.

KEY MESSAGES

- Benefits from mining and impacts on businesses depend on the stage of mining development with different experiences, expectations, and challenges at each stage of the mining process.
- The impact benefit agreement (IBA) and the definition of Inuit ownership affects business development, partnerships and specialization. Both regions are struggling with the proper definition of an Inuit owned business that provides incentives for Inuit leadership and management and ongoing benefits to the regions.
- Preliminary insights indicate that the ability of non-specialized local businesses to partner up with outside companies puts specialized local companies in a vulnerable position. This seems to constrain the level of specialization of Inuit businesses.
- Thirdly, there are unforeseen impacts on migration and the distribution of benefits between local communities and regional hubs. The benefits of mining are distributed differently between communities closer to the mine and larger regional hubs, however this distribution of benefits seems to vary considerably by region and the stage of mining development.
- To date 96 surveys have been conducted throughout Nunatsiavut and Nunavik. In Nunatsiavut, the communities of Makkovik, Rigolet, Hopedale, Nain and Happy Valley – Goose Bay were surveyed while businesses in Kuujjuaq, Salluit and Kangiqsujuaq were surveyed in Nunavik. There are considerable differences in both regions in terms of migration, Inuit employment, the establishment of hubs.
- It is increasingly difficult to recruit Inuit labour to the Raglan mine and the turnover rates amongst Inuit workers are very high. The opposite holds for Voisey's Bay where Inuit labour turnover is low and it is difficult for outsiders to be hired.

OBJECTIVES

We continue to pursue the objectives we identified in our Arctic Net proposal of 2014:

1. To establish a mining impact evaluation method, adapted to the north, that serves to appraise the local economic benefits resulting from the operating mines in Nunatsiavut and Nunavik;

2. To model the dynamics of business economies linked to the Voisey's Bay and Raglan mines;
3. To investigate the dynamics between the land-based and mining-based economies in Nunatsiavut and Nunavik;
    - » After careful consultation with our research partners in Nunavik and Nunatsiavut, we decided to focus on investigating the links between businesses and the mining industry in more depth. Throughout the research process businesses have been very receptive to our survey and expressed a desire to collaborate more. Our primary method of investigating the dynamics and linkages between the land-based and mining based economies was through a household survey but we have been advised, by participants, and research partners that households in these two regions felt over surveyed. Instead, we have opted to acquire the data directly from the mining companies (and not through a lengthy household survey) and from already existing statistical data sets. We will analyze this data with respect to turnover rates, income flows to Inuit households, transfer payments to communities and royalties paid to local governments and Inuit organizations. We will examine to what extent investments are flowing into the land-based economy.
4. To document, examine and interpret the experience of Québec-Labrador Inuit workers and entrepreneurs in relation to economic development and the regions' mining sectors;
5. To provide a comparative analysis of economic and mining developments in Nunavik and Nunatsiavut; and
6. To learn from different experiences with the mining industry in both regions and identify insights for more successful mining policies and impact benefit and resource rent negotiations.

KNOWLEDGE MOBILIZATION

All the activities listed below occurred during 2016/2017:

- Presentation of focus group findings at Nunavik Mining Workshop in Kuujjuaq in April 2016
- Visited Kuujjuaq to pilot survey and encourage participation from more business owners, April 2016
- Visited business in Nain and Goose Bay to pilot survey in May, 2016
- Publication of an article in Arctic Deeply on Economic Development and the Future of Mining in the Canadian North
- Training of local research assistants for administering the business survey in October, 2016
- Administering business survey in Nunatsiavut and Happy-Valley Goose Bay from September 2016 to February 2017
- Presentation at ReSDA annual workshop in Ottawa in October, 2016
- Presentation at Arctic Net annual scientific gathering in Winnipeg in December, 2016
- Administering the survey in Nunavik in February 2017

INTRODUCTION

Resource development from extractive industries are purported to provide economic growth and benefits to local and regional communities. It has been argued that the economic benefits of extractive industries promote economic diversification and inter-sectorial linkages in other areas of the local economy. Yet, non-renewable resource exploitation can also lead to an increase in income inequality within communities, may capture critical human, social and cultural capital, and has the potential to leave behind a harmful legacy on the land (Sandloss & Keeling, 2012; United Nations. Department of Economic and Social Affairs, 2007). Mining induced changes to the territory, lifestyles, and livelihoods thus present potentially adverse effects for the individuals, households and communities affected by these developments, threatening to disrupt the delicate balance and tight interrelations that are characteristic of mixed economies in the North (Bernauer, Kissling-Näf, & Knoepfel, 2000; Rodon & Schott, 2014).

These disparate impacts raise the question of whether the impacts of extractive industries, specifically the mining of non-renewable resources, on local communities is fully understood. In addition, most of the available evidence on the economic impacts of the mining industry is based on regional or national studies. On the local level, mining induced development has been purported to increase the budgets of local communities and increase public spending on infrastructure (Land, Chuhan-Pole, & Aragona, 2015). It should be noted that there are documented cases of negative economic impacts attributable to mining as well (Rodon & Levesque, 2015).

Mining has in some instance led to competition for labor between other industries and increased inequality as the incomes in the mining sector increase relative to the incomes in other sectors (Rolfe, Gregg, Ivanova, Lawrence, & Rynne, 2011). Furthermore, there are flow-on effects such as an increase in housing prices. The Real Estate Institute of Western Australia reported a 11.9% annual increase in housing prices as a result of approximately 1000 new arrivals within the mining sector per week in Perth, Australia in 2013 (Brueckner, Durey, Mayes, & Pforr, 2014). With respect to the infrastructure improvements attributable to the mining sector there are concerns that the improvements serve the exclusive interests of the extractive industry at the expense of other local interests (Fessehaie & Morris, 2013).

It has been argued that the economic impacts of mining are felt more on the regional scale as opposed to the local scale (Ejdemo, 2013). The veracity of this claim will be tested in the context of the Canadian sub-arctic. Whether the theories of resource development and economic growth apply in the context of the Canadian sub-arctic is another contested question. The presence of indigenous populations in the resource rich Canadian arctic and sub-arctic also raise questions of local indigenous participation in economic development. While there are unanswered questions about the impact of extractive industries on local economic development, the impacts on business development are even more under-researched (Kemp, 2010). Case studies highlight impacts and activities at particular locations or by different companies, but comparative or evaluative research about community development, either by region, commodity, country, or otherwise is rare and the lack of research about local-level practice in mining reflects the general trend that local small business development remains profoundly under-researched (Kemp, 2010).

The purpose of this project is to establish the role of extractive industries in economic development outcomes, specifically human and business development, within the context of the Canadian sub-arctic. The project will assess what the economic impacts of mining are, how these impacts are felt locally or regionally, and what benefits arise for local businesses and employees at different stages of the mining process. A comparative analysis will investigate differences in experiences, benefits and challenges in Nunavik and Nunatsiavut, and inform insights for more sustainable development paths, improved impact benefit agreements and labour, training and mining policies.

ACTIVITIES

At the end of April, 2016 the research team went to Kuujjuaq, Quebec to attend the annual mining workshop. At this workshop, preliminary results from focus groups held the previous year were presented to business owners and other attendees. During this trip, the research team took the opportunity to pilot the survey with several businesses in Kuujjuaq and finalize the design on the business survey.

In May, 2016 the business survey was piloted in Nunatsiavut. Initially business owners in Happy Valley-Goose Bay (HVGB) were contacted with the aid of the Nunatsiavut Government and surveyed. In addition to business owners in HVGB, business owners in Nain were also surveyed. These piloted surveys served two purposes. Firstly, it allowed the research team to assess the survey and finalize its design. These piloted surveys also provided preliminary results that were consistent with some of the themes that emerged in the focus groups from the previous year.

From June – October 2016 the business survey was administered in the communities of Nain, Makkovik and Rigolet. A local research assistant was hired through the Nunatsiavut Government to aid in contacting potential participants and in surveying these participants. From November 2016 to March 2017, the survey was administered in HVGB, Hopedale in the Nunatsiavut region and in Kuujjuaq, Salluit and Kangiqsujuaq in the Nunavik region. An additional local research assistant was hired to aid in this process in both Nunatsiavut and Nunavik. To date 96 surveys have been administered across the two regions. These surveys were conducted in person and each survey took at least 90 minutes to complete. There are a few scheduled surveys that need to be conducted in Nunatsiavut before the process is complete.

In addition to these business surveys, Statistics Canada data on human development in both Nunavik and Nunatsiavut were collected and analysed. The results of this analysis are summarized in the results section. Additional focus groups were conducted with Inuit employees in Nunavik who work at the Raglan and Canadian Royalties mine.

The findings from the business focus groups, which were conducted in 2015, were presented at the ReSDA workshop by the PI Stephan Schott in Ottawa in October 2016. In addition to this presentation, a member of the research team (Anteneh Belayneh) participated in a ReSDA panel on economic development in Norther Canada. The annual Arctic Net scientific gathering was held in December, 2016 in Winnipeg. The research team was part of a session on the Mining Industry and Indigenous Communities and Anteneh Belayneh provided a presentation on the preliminary results of the surveys that had been conducted to date.

RESULTS

The results to date point to three distinct themes concerning mining induced development in the Nunatsiavut and Nunavik. The three themes are the importance of the stage of mining development and its impact on businesses and economic development, the impact of the IBA on specialized local, indigenous companies and the differing developments between communities closer to the mine site and the regional hubs.

1- Stage of Mining Development

Participants in the focus group sessions identified the importance of the exploration phase to both business and community development. Businesses alluded to the fact that communities in Nunavik and Nunatsiavut benefited most during this phase of development. Ejermo (2013) identified three distinct types of benefits that are derived from extractive industries. These benefits are direct, indirect and induced benefits (Ejdemo, 2013). Direct benefits consist of employment opportunities generated at the mine, while indirect benefits incorporate employment opportunities that are generated in supplying the mine (Ejdemo, 2013). Induced benefits are derived from the consumption surrounding mining development and the employment opportunities that are sustained by this consumption (Ejdemo, 2013).

In singling out the exploration phase as the most beneficial to their community, participants from Nunavik and Nunatsiavut were alluding to the importance of induced benefits. During the exploration phase, a small community near a mining site would have to lodge and accommodate those employees that participate in exploration activities. Thus, consumption, in the form of accommodation and meals for example is prevalent. These induced benefits occur concurrently to direct benefits in the form of employment.

Unlike the exploration phase, the construction phase requires a greater amount of labour input. As such, the opportunity for direct employment at the mine is greater. With respect to businesses, the construction phase could result in greater competition for labour between them and the mine site and can especially impact the wages that businesses must pay to attract and retain employees. Deriving direct and indirect benefits during the construction phase for businesses is highly dependent on the type of business. Businesses that can supply construction camps can benefit from this stage of development. Businesses that derived induced benefits during the exploration phase may suffer as the economic activity is concentrated at the mine site as opposed to local communities.

During the construction and operational phases at a mine, the labour force is usually flown in and out and may completely bypass the local communities. Businesses in these locales that depend on consumption will not greatly benefit from the large construction crews at a mine site because these crews are not lodged in these communities while working. A portion of the workforce at Voisey's Bay and Raglan are from the surrounding local communities. The wages these employees derive from their jobs may result in greater consumption in their communities. However, a greater percentage of the workforce never sets foot in these communities. The data from Voisey's Bay indicates that most of the employees are not from Nunatsiavut and cannot consume in the communities closer to the mine and generate induced benefits. In addition, the consumption opportunities of the returning workers are limited by what is available in their communities. If returning workers are consuming products that are unavailable in their communities, the money generated by the mine is flowing out of the communities and benefiting non-local businesses in different locales.

The major contrast between the three phases of mine operation on business development is that only the exploration phase results in a significant level of induced consumption in the communities close to the mine. The construction and operational phases employ a greater number of people but unless businesses are involved in supplying the labour force, businesses do not necessarily benefit. Finally, with respect to the consumption by individuals returning to their communities, a lack of available products or services could lead to the consumption of non-local products and the flow of benefits away from these communities. The benefits of mining flowing out of the closest communities was a concern expressed by participants from both Nunavik and Nunatsiavut.

2- The IBA, Partnerships and Specialization

The Impacts and Benefits Agreements (IBA) that were signed because of the Raglan and Voisey's Bay mines were designed to ensure that the local communities would benefit from the operations. The Raglan IBA in 1995 was the first of its kind in Canada. At the focus group sessions, business owners from Nunavik indicated that at the time the IBA process was new. The IBA at Voisey's Bay came a lot later and certain lessons might have been learned by then. Participants from Nunatsiavut indicated that the IBA had a positive impact on their businesses and incentivized Vale to give local companies the opportunity to procure contracts. While the IBA's preferential treatment of local, indigenous companies is laudable and necessary it does contribute to difficulties for specialized companies. With the help of our business survey we will be able to evaluate further how the IBA has been beneficial for different kind of businesses at different stage of the mine in both regions.

One ubiquitous complaint from participants from both Nunavik and Nunatsiavut was the formation of partnerships with Southern companies. These partnerships or joint ventures are typically 51% owned by an indigenous beneficiary. However, these companies are sometimes operated by non-local and non-indigenous individuals who successfully procure contracts from Vale or Raglan to the detriment of other local companies. Participants from Nunatsiavut insisted that 51% ownership should not be enough to qualify as a registered Inuit business and being involved in the operation of the business should be considered as well. The reality described by focus group participants seems to be an environment where local businesses are competing with some Inuit owned partnerships and joint ventures with more experienced and capital cushioned Southern companies. Our survey will further examine how predominant this issue is.

The focus group discussions and a pilot version of the business survey revealed that companies compete on all the contracts related to mining, irrespective of their specialization. This phenomenon leaves highly specialized, local Inuit companies at a disadvantage. The IBAs with both mines stipulate that 51% indigenous ownership of a business qualifies that business to be on the Inuit business registry and can procure a contract from the mine. Thus, non-local, non-Inuit companies form partnerships with Inuit beneficiaries to be on the Inuit business registry and successfully procure contracts. Specialized Inuit businesses must compete with non-local companies and with local, non-specialized Inuit companies. What is also apparent is that local non-specialized businesses on the registry, seek out various partnerships with non-local companies to stay competitive and secure contracts. These contracts are not necessarily in the areas where these businesses specialize. The non-local companies benefit from these partnerships because they need Inuit partnerships to secure contracts, as stipulated in the IBA. The non-specialized local companies benefit by using their beneficiary status to partner up with other companies and secure contracts in areas they have not necessarily invested in. Our business survey will provide concrete results that can form the basis for a discussion of contract allocation and the definition of an Inuit owned business for each region.

3- Regional Hubs vs. Local Development

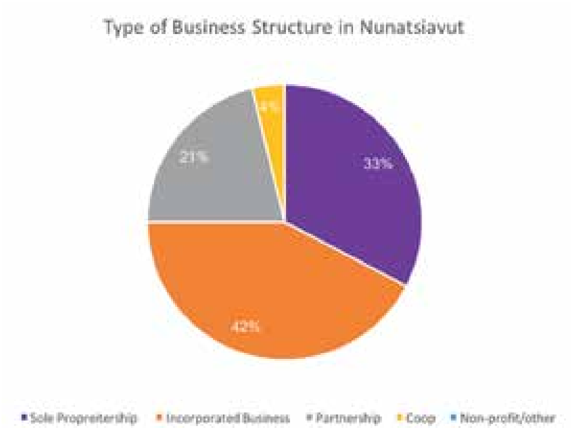
Ejdemo (2013) also espoused that the economic impacts of mining differ depending on a local or regional scale of analysis (Ejdemo, 2013). Indirect and induced benefits are anticipated to be higher on a regional level because the regional business structure is better equipped to supply inputs to mineral development projects and the benefits are enhanced by the impacts from commuters who pass through the regional hubs (Ejdemo, 2013). This theory is consistent with some of the results from the focus group sessions. As mentioned earlier, participants from smaller communities closer to the mine, specifically Nain, highlighted the importance of the exploration phase. In addition, the number of commuters who passed through the smaller communities was not enough to generate induced benefits through consumption after the exploration phase. When discussing the regional hubs, HVGB and Kuujjuaq, participants, especially from Nunatsiavut, described how the hubs are important centers for the training of employees. Some of the participants had businesses highly dependent on the consumption of mining employees. We now also have preliminary business survey results to add to this discussion.

4- Preliminary Survey Results

Our framework for analysing the results of the surveys was comparative in nature. These surveys have revealed that 88% of businesses in Nunatsiavut are on the Inuit business registry while only 48% of the businesses are on the Makivik business registry. Businesses in both Nunavik and Nunatsiavut exhibited a similar proclivity for entering partnerships or joint ventures. Forty-two percent of businesses in Nunavik and 42% of businesses in Nunatsiavut had either partnerships or joint ventures respectively. The businesses in the two regions are structured differently (Figures 1A and B).Sixety-four percent of businesses in Nunavik are incorporated, by far the most common type of structure in the region. Incorporated businesses are the most common type of business structure in Nunatsiavut as well but the percentage is much lower (42%). A third of the businesses in Nunatsiavut are sole proprietorship which is significantly more than in Nunavik where only 8% of the business are sole proprietorships.

One of the purported benefits of the mining industry is the opportunities afforded to potential employees. These jobs are purported to be high paying and are among the most widely identified direct benefits of the mining industry. Since the surveys were not conducted at the mine, but rather with businesses who have procured or are attempting to procure mining contracts or derive induced benefits, the benefits from employment identified are indirect or induced

a)



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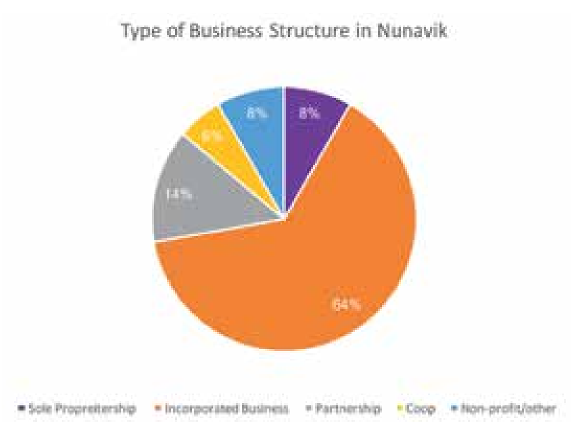

Figure 1. a) Nunatsiavut and b) Nunavik business structure.

benefits. A large proportion of the businesses surveyed in both Nunavik and Nunatsiavut are relatively small and employ 10 or less employees. In Nunavik, 72% of the businesses employ 10 or less full time employees and this number is 77% in Nunatsiavut. With respect to Inuit employment, 53% of the full-time employees of Nunavik businesses are Inuit with only 34% being Inuit in Nunatsiavut. Further analysis of this discrepancy reveals that the difference largely derives from Inuit employment in larger companies. Full-time Inuit employment in companies with 10 or less employees are very similar between the two regions. In both regions, over half of the employees in these small companies are Inuit, 56% in Nunavik and 55% in Nunatsiavut respectively. However, in companies with more than 10 employees, the percentage of Inuit employees in Nunatsiavut is only 31% while the percentage remains relatively the same as for small companies in Nunavik (52%) (Figure 2).

The dependence of businesses on mining or mining related activities for their revenues was very low in both regions (Figure 3). Only 17% and 21% of companies' revenues, in Nunavik and Nunatsiavut respectively, was generated from mining related activities. Surprisingly, a large percentage of the companies in both regions derived less than 1% of their revenues from mining related activities. In Nunavik 42% and in Nunatsiavut 58% of companies make less than 1% of their revenues from mining related activities.

These figures call into question earlier findings from the focus groups that emphasized the participants' positive reaction to the mining industry as an economic driver for growth. These figures indicate that the mining industry is not a significant revenue generator for a significant proportion of the companies in these generators. These revenues do not incorporate any induced benefits that businesses can accrue from induced consumption in their products. It does, however, reveal that a significant portion of companies have not been able to accrue direct or indirect benefits. These preliminary findings could call into question whether businesses accrue meaningful benefits from mining. Seventy percent of the revenues of businesses,

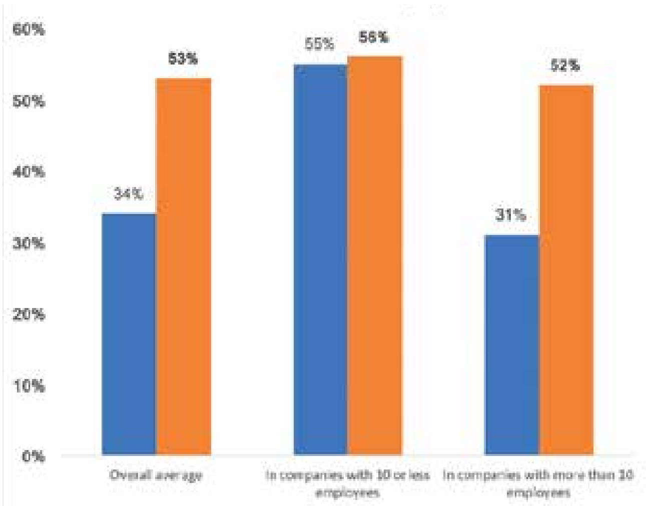

Figure 2. Level of full time employment at companies in Nunatsiavut (blue) and Nunavik (orange).

in both Nunavik and Nunatsiavut, are not related to mining related activities. Any mining related policy in these regions or other regions must incorporate these findings if local businesses are a priority with respect to accruing benefits and revenues from mining related activities.

5- Human and Community Development with the Raglan Mine

The direct economic benefits of the Raglan mine on the communities of Salluit and Kangiqsujuaq were analyzed as part of this study. This research provided an initial analysis of the ways Raglan operations have impacted socio-economic dimensions in the two communities. The theoretical model used in this study broke down mine operations in terms of employment, wages, purchases of goods and services, royalties, mining taxes and investments and their effects on the following dimensions: demographics, employment, education, training and housing. The employment rate rose between 1996 and 2001 in Salluit (+2.6%) and Kangiqsujuaq (+4.1%) while falling in the rest of Nunavik (-3%). During this time period, employment growth in both communities may have been linked to the opening of the Raglan mine. Nonetheless, between 2001 and 2011, rates fell in Kangiqsujuaq (-0.9%) while rising in Salluit (+4.4%) and in the rest of Nunavik (+3.6%), with the result that these employment rates are tending to converge.

This data shows that the participation rate rose between 1996 and 2001 in Salluit (+5.6%) and Kangiqsujuaq (+7.6 %) while falling in the rest of Nunavik (-2.1%). Over a longer time span, between 1991 and 2001 it rose sharply in Kangiqsujuaq (11.4 %) and Salluit (16.4%) while varying a little in the rest of Nunavik (+4%) (Figure 4). It then remained higher in both communities than in the rest of Nunavik from 2006 to 2011.

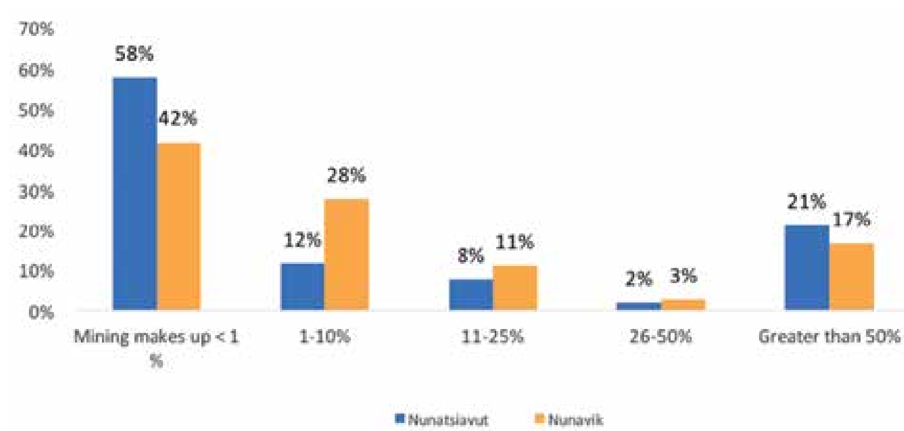

Figure 3. Revenues derived from mining.

Regarding employment specifically in the mining sector (Figure 5), the data show that employment was much higher in Salluit and Kangiqsujuaq than in the rest of Nunavik between 1996 and 2011. This trend however strongly decreases around 2001, when they are only between 1.7% and 2.4% higher in Salluit and Kangiqsujuaq, respectively, than in the rest of Nunavik.

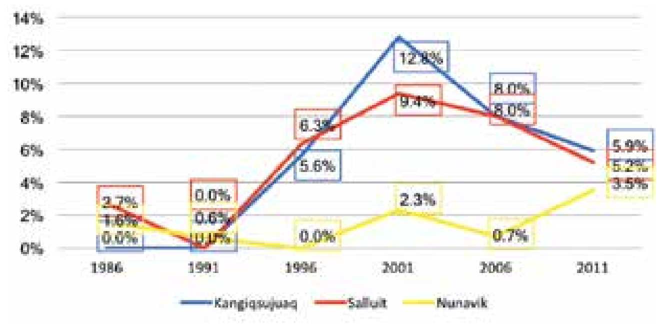

Figure 5. Proportion of employment in the mining sector.

This analysis on the impacts of the Raglan mine on these two communities can be summarized as follows:

- The opening of the Raglan mine and the mining operations did not seem to affect the Demographic dimension.
- The Employment rate rose in Salluit and Kangiqsujuaq while falling in the rest of Nunavik between 1996-2001. The mine opening is related to a higher proportion of jobs in the mining sector for the two nearby communities than for the rest of Nunavik. However, the Raglan mine does not appear to have had an important impact on the job market dimension in the most recent years.
- Regarding Education, the Raglan mine seems to be linked to a slightly higher rate of graduation in Salluit (+1%) and Kangiqsujuaq (+5%) than in the rest of Nunavik (-2%) for the 1996-2001 period. This proportion then rose more sharply in Salluit (+26%) and Kangiqsujuaq (+26%) than in the rest of Nunavik (+21%) between 2001 and 2011 (Figure 6). This could be related to the implementation of a local training program targeting mining employees. These education levels refer to individuals in Nunavik, 15 years or older, who hold either a high school or post-secondary degree.
- For the Income dimension, the analysis suggested that the Raglan mine helped to slightly increase mean and median household incomes in the two communities, compared to the rest of Nunavik. However, because available statistical data was incomplete, this dimension remains difficult to analyse, and we will further investigate with the Raglan Mine.
- Data was also incomplete for Housing, but findings however suggest that the mine had no impact on this dimension.

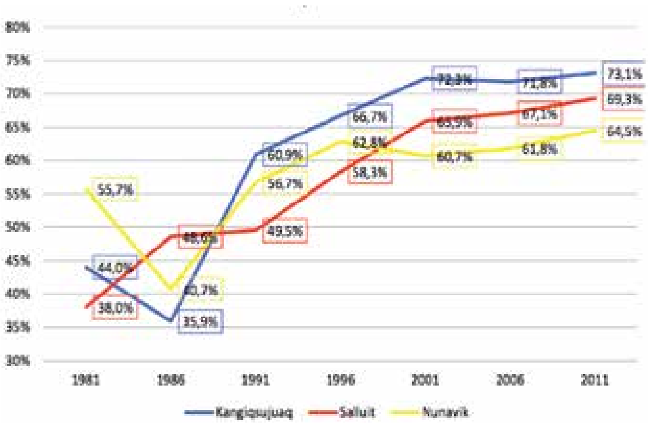

Figure 4. Labour participation rates in Nunavik (1981-2011).

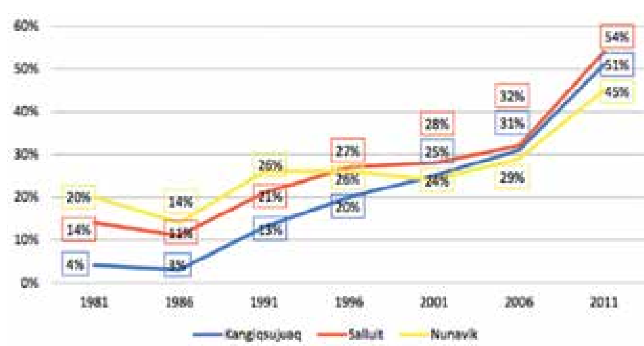

Figure 6. Percentage of individuals (15 -24 years old) with degrees in Nunavik.

Focus groups conducted with Inuit employees at Raglan have revealed that they find the work at the mine very challenging mostly because of the fly-in, fly-out schedule. Employees also have indicated a strong feeling of membership that was forged at the mine with their fellow employees, both Inuit and non-Inuit. Though Inuit and non-Inuit workers clearly interpret mine work in a similar way, the integration into the work environment remains more challenging for Inuit workers, who are faced with a double-challenge: The challenge of adapting to working conditions and the cultural challenge of integrating into a system of Western norms, rules and structures that are often unfamiliar to them. Inuit workers therefore often perceive the effort and energy necessary to operate successfully in the mine environment quite challenging.

6- *Human and community development with the Voisey's Bay mine*

With respect to the Voisey's Bay operations and processing, in 2014, approximately 42% of the employees were Inuit (Figure 7). Fourteen percent of the employees reside in the five communities of Nain, Hopedale, Makkovik, Postville and Rigolet while 21% of the employees reside in Happy Valley-Goose Bay. The wages these employees derive from their jobs may result in greater consumption in their communities. However, a large proportion of the workforce never sets foot in these communities. The data from Voisey's Bay indicates that most of the employees are not from the five communities within Nunatsiavut (Figure 7). This economic leakage indicates that the money generated by the mine is flowing out of the communities resulting in very limited positive direct income flows to households in Nunatsiavut communities.

The human and community impacts of Voisey's Bay are somewhat mixed. Most the income in Nunatsiavut is generated at Voisey's Bay (Figure 8). Over an eight-year period, more than 70% of all income in each of the five communities within Nunatsiavut was generated at Voisey's Bay. These numbers tend to indicate a great dependence on Voisey's Bay.

The participation rate and employment rates increased in Nunatsiavut between 1991-2011. Over the 20-year period, employment rates and participation rates have increased in all five communities except for Nain. Figure 9 shows the evolution of labour participation rates in all the communities where labour participation remained relatively stable and slightly declined in Nain.

Table 1 depicts the employment rates in each of the five communities from 1991-2011. Voisey's Bay mine started its construction phase in 2001. The employment rate in 2001 was higher than the rates in 1991 or 1996 in all the communities but Nain. Since 2001, the employment rates have continued to increase in all the communities except Nain and Postville.

While these statistics indicate a positive impact from the presence of the Voisey's Bay mine the fact that unemployment rates have risen over the same period offers a contrarian view (Figure 10). Unemployment rose by 43% over a 20-year period and peaked in 2006 after the construction phase at the Voisey's Bay mine ended.

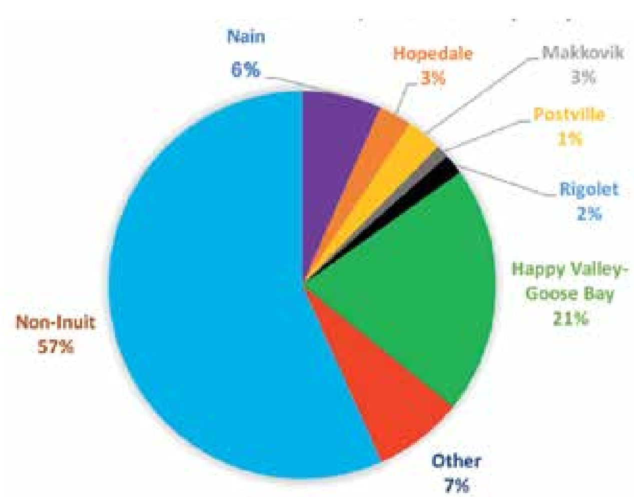

Figure 7. Employment figures from Voisey's Bay (2014).

Table 1. Employment rates (%) for Nunatsiavut communities (1991-2011).

Community	1991	1996	2001	2006	2011
Rigolet	31.1	30.6	34.7	34.9	37.5
Makkovik	31.1	36.5	38.2	36.8	43.9
Hopedale	28.6	33.8	38.6	35.1	41.4
Nain	46.2	45.3	43.4	41.3	42.1
Postville	35.3	43.8	48.4	42.4	46.9

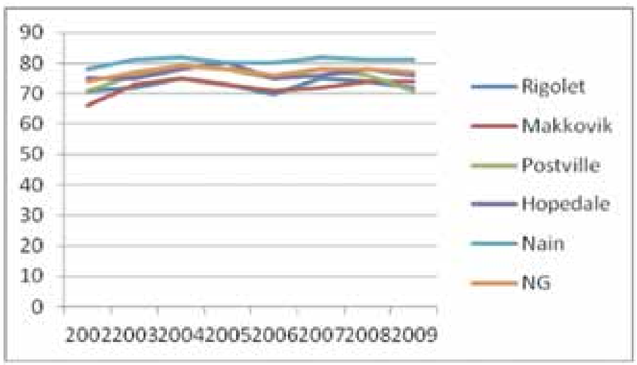

Figure 8. Percentage of income in Nunatsiavut generated at Voisey's Bay (2002-2009).

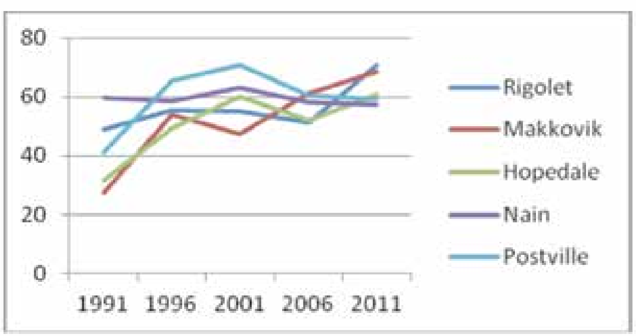

Figure 9. Labour participation rates in Nunatsiavut (1991-2011).

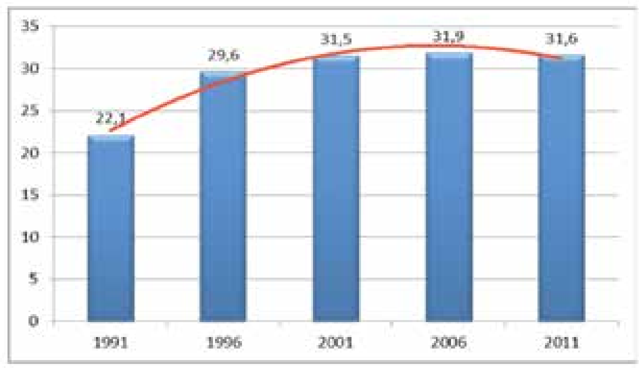

Figure 10. Unemployment rate in Nunatsiavut (1991-2011).

DISCUSSION

Our analysis to date has concentrated on two fronts, the study of the economic impacts of mining, especially on local businesses, and the human and social impacts on local communities that occur due to mining. Our analysis followed these two streams in both Nunavik and Nunatsiavut. Our analysis was comparative in nature and highlighted some important distinctions between the two regions. With respect to business structure, most of the businesses in Nunavik are incorporated with very few sole proprietorships, whereas a third of the businesses are sole proprietorships in Nunatsiavut. The extent to which businesses are affiliated with their business registries in the two regions differs greatly and the fact that the business registry is being revised in Nunavik may alter the figures reported from our survey in the future.

Our study to date has shown that the impacts of mining on businesses is still a contested question. 70% of the companies surveyed in both Nunavik and Nunatsiavut only receive up to 10% of their revenues from mining. The next step in our analysis is to determine at what stage of the mining process these revenues are accrued, and how the revenues are distributed among companies in the region and outside the region and local households (in terms of employment income). One of the themes identified in the focus groups from 2015 was that the impacts of mining differ depending on the stage of mining development. Our goal is to further analyse and identify at which stage of mining these businesses receive most of their benefits.

The definition of an Inuit business is something both jurisdictions are struggling with. In both regions, it is not clear what an accepted and operational definition of an Inuit owned business is. This has implications for Inuit owners' control of businesses, the degree of specialization in specific mining related service sectors and the partnering up with Southern owned businesses. We, therefore, will create an Inuit Business definition database that considers all local policies, criteria and application forms. We will discuss a more specific and refined definition of an Inuit owned business in each region, and how to devise a more effective application process that could allow more involvement of locally owned businesses in mining contract bidding and the execution of contracts.

The participation rates in both regions has increased since the opening of the Raglan and Voisey's Bay mine respectively. The presence of these major mining projects has, however, not necessarily translated to high employment figures in the local communities. Indeed, in Nunatsiavut unemployment rates have increased while Voisey's Bay was undergoing the construction phase of its development. How employment opportunities trickle down to the local communities is another dimension that will be analysed going forward. Through comparative analysis and consultation with our regional and local partners we will explore how employment opportunities could be improved and how turnover rates of Inuit employees could be reduced.

CONCLUSION

Mining is purported to generate induced consumption that benefit local businesses and local communities (Ejdemo, 2013). It appears the exploration phase resulted in the most induced benefits to the local communities. Once the construction and operational phases began, the communities were faced with the flyover effect where workers just flew in and out of the mine site and bypassed the communities, reducing the benefits of induced consumption. Although mining has increased economic activity in both regions in terms of revenue flows to businesses and labour participation rates it is not clear to what extent communities close to mining sites have benefitted over time. Inuit employment at the mine varies considerably between regions and does not seem to benefit communities closer to the mine as much as other communities. A detailed analysis of our business survey with follow up workshops and closer analysis of the employment, income and revenue flow data will provide some answers to these important questions.

Mining is playing and will play a major role in Northern communities in the future with a transition to a low carbon economy that will require significant increases in the mining of copper, cobalt, rare earth metals, and other minerals that are abundant all over Canada's North. To get the most out of mining activities for Northerners and their communities we need to better understand what the potential economic benefits are and how they can be maximized. Our understanding of the dynamics of mining activities, local business creation and development, as well as household well-being and the impacts on subsistence harvesting is very limited. However, our current work has enlightened us to the importance of the stage of mining development and what type of benefits coincide with each stage. With our project, we wish to contribute to a better understanding of this subject and to start a very necessary, open and transparent conversation. We will further analyse experiences of businesses and household in both regions. We will then discuss and evaluate how governments, policies and actions by mining companies can better assist businesses and households to succeed with business and employment opportunities and the fulfilment of IBA promises in the future.

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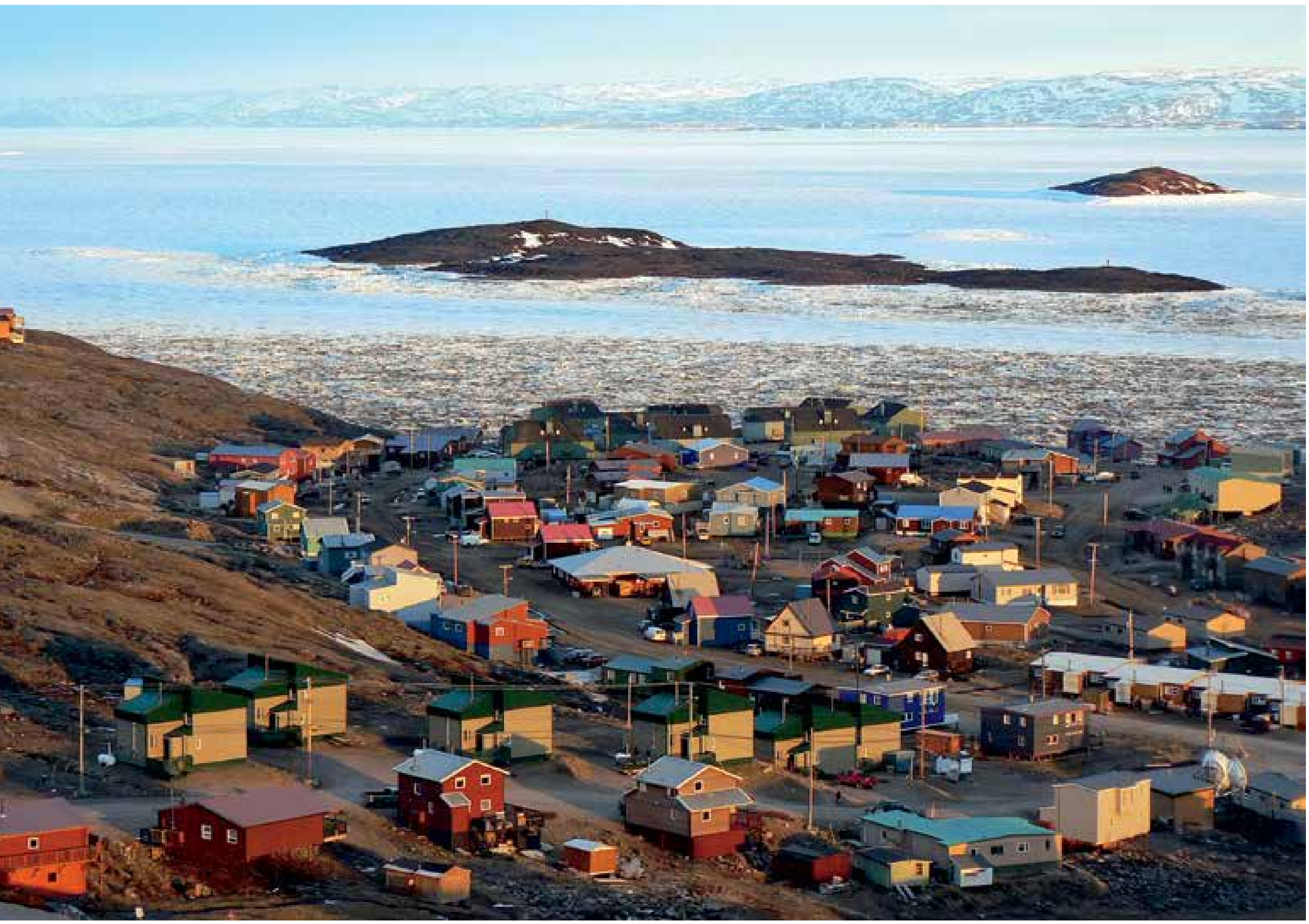
SECTION V. KNOWLEDGE TRANSFER



Section V is composed of four ArcticNet research projects focussing on knowledge mobilization in support of sustainable development in the Canadian Arctic.

KNOWLEDGE CO-PRODUCTION FOR SUSTAINABILITY IN CANADIAN ARCTIC COASTAL COMMUNITIES

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ABSTRACT

The goal of this project is to develop a network of community knowledge centres, accessible and relevant to northern residents, that support monitoring and analysis of environmental and social conditions to meet information needs for local and regional planning, while addressing local priorities. The network will be initiated in a number of communities and regions such as the Inuvialuit Settlement Region (ISR), Kitikmeot (Kugluktuk or Cambridge Bay), Kivalliq (Arviat), Baffin (Clyde River), and Nunatsiavut, locations in which the participants in this proposal have recent or ongoing involvement and local partnerships. As the Canadian component of a larger, circumpolar, coastal communities network (CACCON), this will complement and enhance existing community- and regional-based initiatives, facilitating peer-to-peer communication and knowledge-sharing with partner centres around the Arctic. In addition to the development and proof-of-concept of CACCON, the project will support key components of ongoing and future observing and change detection functions, including marine climate (winds, waves, sea ice), visibility (fog, blowing snow, smoke), coastal hazards (breakup and storm-surge flooding, shoreline erosion, ice pileup, local tsunami risk), landscape hazards (slope failure, active-layer deepening, excess ground ice and thaw consolidation), supported by digital imagery and mapping data. These issues address a broad range of challenges for transportation, built infrastructure, healthy homes, preservation of culturally important sites, safe sea-ice travel, and food security. Key components of the project include: coastal sensitivity to climate change and coastal community vulnerability; cost of adaptation mapping, coastal climate, and coastal archaeological resources risk assessment. The project will provide training for at least seven graduate students (PhD and MSc) and capacity building in northern regions and communities through youth involvement and technical staff in the ISR and Nunatsiavut.

KEY MESSAGES

- There is a growing need for locally applicable decision-relevant knowledge from multiple sources in Arctic coastal communities and regional or territorial governments in the Canadian Arctic and other circumpolar jurisdictions. CACCON, the Circum-Arctic Coastal Communities KnOwledge Network, was active on many fronts promoting the development of knowledge management capacity in northern centres.
- CACCON serves as the operational component of the Arctic Regional Engagement Network for Future Earth Coasts. This was recognized through establishment of a coordination office with support from ArcticNet, Future Earth Coasts, and Memorial University.
- Territorial government agencies and regional indigenous organizations and governments host substantial technical expertise but require specialized scientific partnerships to address priority issues, including environmental challenges such as coastal erosion, flood risk, navigation support (harbour development), permafrost degradation affecting provision of safe and adequate housing and major development projects (hydrocarbon exploration, mine development, reservoir construction).
- Despite several initiatives, capacity for co-production and mobilization of knowledge to support goals of sustainable development remains limited in most places.
- A promising approach to address this capacity gap is to support the foundations for 'research readiness' at the community level, recognizing that this can promote knowledge management capacity, economic development, and other sustainability goals.
- Expansion of our ice and flood monitoring and reporting during the 2016 breakup in the Mackenzie-Beaufort region to incorporate an

active Facebook group, managed by northerners for northerners, increased participation to over 450 and provided a forum for sharing on-site knowledge of events as they unfolded.

- SmartICE is well established in Nain and Pond Inlet, making critical information on sea-ice conditions readily available to members of the community heading out on the ice and contributing to self-confidence and knowledge-management capacity in both communities.
- SmartICE Inc., recipient of the 2016 Arctic Inspiration Prize, is being incorporated as a social enterprise to benefit partner communities while allowing for expansion to a wider network in a financially sustainable way.
- There is a cost of climate-change adaptation for the housing sector in both Old Crow YK and Arviat NU; and when the impact of climate change is considered, some foundations become more cost-effective than others and space-frame foundations have expected lifetime costs of climate change 4-15% lower than other foundation types.
- Communities in the Inuvialuit Settlement Region show distinct variations in the occurrence of fog and low visibility depending on location. Sachs Harbour, in particular, stands out as particularly foggy. There are distinct patterns of large-scale weather that have been found to favour occurrences of fog, leading to improved capability for forecasting low-visibility events.

OBJECTIVES

The goal of this project is to pilot a network of community knowledge centres, accessible and relevant to northern residents, that provide the capacity for integrated situational monitoring and analysis of physical/ecological and social conditions at local and regional levels to inform effective decision-making and transitions to more sustainable futures. We continue to pursue this primary objective, addressing the following milestones during the current reporting year:

1. Promote knowledge centre development and community data management and accessibility capacity in Arctic coastal communities.
2. Grow networking, communication, and peer-to-peer capacity sharing across the Canadian Arctic and circumpolar CACCON network.
3. Explore and develop preliminary transdisciplinary indicators and pursue related development and testing of CanCoast vulnerability tool.
4. Make high-resolution, multi-nested, atmosphere-ocean-ice model forecast output suitable for community use and accessible to users.
5. Advance cost-of-adaptation analysis in pilot communities.
6. Facilitate SmartICE workshops in selected communities.
7. Report on landscape instability and sediment dynamics in pilot communities.
8. Compile initial insights from CACCON on the contribution of knowledge co-production in Arctic coastal communities to building capacity and resilience.

KNOWLEDGE MOBILIZATION

This project is primarily focused on knowledge mobilization for local decision-making. A number of specific activities during the year have addressed the need for knowledge mobilization at scales from local to circumpolar:

- >30 interviews with on-line, print, and broadcast media
- Mentoring of northern research employees in Nain and Pond Inlet and northern partners in other communities in Canada and Alaska

- Invited presentation on CACCON to Future Earth, Bern, June 2016
- Special session at Canadian Association of Geographers Conference, Halifax, June 2016
- Invited presentations on CACCON and SmartICE to Arctic-COAST Workshop, Murmansk, June 2016
- Invited keynote presentation to the renewal of the Arctic Coastal Dynamics Project, Potsdam, June 2016
- Invited contribution to the Standing Senate Committee on Aboriginal Peoples with reference to best practices and on-going challenges relating to housing in First Nation and Inuit communities
- Invited participation in the National Housing Strategy Expert Roundtable on Indigenous Rural and Remote Housing
- Special Session at Inuit Studies Conference on 'Bridging Traditional Knowledge and Western Science to Address Community Research Priorities', co-convened with community partners from Arviat and Pond Inlet NU, October 2016
- Hosted Forum on Social Licence to Operate in the Arctic, St. Johns NL, October 2016
- Workshops on traditional knowledge and SmartICE, Pond Inlet, NU, February 2017
- Workshop on sea ice, SmartICE, and navigation hazards with Baffinland, Pond Inlet, February 2017

INTRODUCTION

Canadian Arctic and sub-Arctic Inuit communities are almost exclusively located in coastal settings that provide access to marine and terrestrial food resources, transportation and communication corridors, and culturally significant landscapes. These coastal communities and their critical infrastructure are also exposed to a range of coastal and marine hazards in addition to landscape hazards common throughout the permafrost regions of Canada. The coastal zone is the locus of complex interactions among marine, terrestrial, and atmospheric processes and thus is particularly sensitive to ongoing and projected environmental change, exacerbated by anthropogenic stressors (Forbes 2011). Combined with challenges of economic and social development, demographics, globalization, mixed cash and non-cash economies, maintenance of linguistic and cultural integrity, health, and well-being, the already-noticeable effects of environmental change are an added source of uncertainty and concern. Coastal archaeological sites in Arctic Canada are also under threat, with important knowledge of the region's history and prehistory potentially lost to erosion. Climate change will exacerbate existing coastal hazards, leading to more rapid loss of archaeological resources and culturally significant sites in the future. All of these factors represent potential vulnerabilities and challenges to health and safety, community resilience, cultural integrity, sustainability, and well-being. This project is based on the conviction that an integrated, collaborative, and holistic approach to monitoring, understanding, and managing the many sources of change in northern communities is a key to local empowerment and sustainable development for present and future generations.

ACTIVITIES

CACCON

(Bell, Forbes, Slaney, Le Tissier, Riedlsperger, Larsen, Elverum, Radosavljević, Pulsifer, Petrov, Kraev, Couture, Manson)

- CACCON was confirmed as the primary operational component of the Arctic Regional Engagement Network of Future Earth Coasts (www.futureearthcoasts.org). With contributions from Future Earth Coasts and Memorial University, a network coordinator (Slaney) was hired to facilitate communications and network activities, while documenting the engagement process and enablers of research co-design and knowledge co-production in CACCON hubs (see caccon.org).

- Management of the network was coordinated with the International Project Office of Future Earth Coasts (University College Cork, Ireland) and an interim advisory committee including representatives of northern communities, other networks (ELOKA), other parts of the circumpolar Arctic and early-career researchers, while maintaining contacts in pilot communities and other northern partners.
- CACCON and Future Earth Coasts jointly convened a stakeholder engagement workshop at the Arctic Science Summit Week 2016 (March 2016). Jointly sponsored by ELOKA (Exchange for Local Observations and Knowledge of the Arctic) and Arctic-COAST, this workshop brought together government officials and community knowledge holders from seven communities in three Arctic countries (Russia, USA, Canada), with academic partners and representatives of other networks (CACCON, 2016).
- Consultation, engagement, trust-building, and information sharing activities were undertaken in at least 15 communities in Russia, USA, and Canada (Inuit Nunangat).
- CACCON promoted local knowledge co-production and mobilization: through social-media information sharing and public data access training in the Inuvialuit Settlement Region; through SmartICE pilot projects with local indigenous management in Nain (Nunatsiavut) and Pond Inlet (Nunavut); through landscape mapping and cost-of-adaptation research in Arviat (Nunavut) and Old Crow (Yukon); and through scientific and moral support of indigenous health priorities requiring contaminant mitigation (Lower Churchill hydropower reservoir, Labrador).
- The activities and philosophy of CACCON were presented, by invitation, at the Future Earth annual meeting (Bern); International Conference on Permafrost (Potsdam); Arctic-COAST Workshop (Murmansk); Coastal Expert Monitoring Group of the Circumpolar Biodiversity Monitoring Program (Ottawa); as well as in sessions at the Canadian Association of Geographers (Halifax) and the Inuit Studies Conference (St. John's NL). CACCON was also invited to the MEOPAR Response core 'Communities of Practice' workshop (Ottawa) and to the Polar Connections Interoperability Workshop and Assessment Process (Rome).
- The CanCoast initiative explored various approaches to the development of a climate-change vulnerability index based on an existing index of physical shoreline sensitivity; also assembled demographic and other data sets, and initiated discussions with the community of Pond Inlet on the desirability and feasibility of a downscaled CanCoast application for the community, with a focus on community priorities for geospatial information management.

SmartICE

(Bell, Ljubicic, Braithwaite, Dawson, Briggs, Wilson, Arreak, Angnatok, Laing, Elverum)

- The SmartICE project continued to operate in Nain (Nunatsiavut) and completed its first full winter of operations in Pond Inlet (Nunavut).
- Community project coordinators (operators) were employed in both communities and ensured the availability of fixed and mobile sea-ice thickness and roughness information for decision-making for safe travel on the ice by members of the community accessing country food.
- The SmartICE web-based sea-ice information portal developed by EMSAT was launched in the 2016 sea-ice season.

Cost-of-Adaptation Mapping (CAM)

(Bell, Forbes, Riedlsperger, Bagnall, Perrin, Lee, Tagalik)

- Surficial geology mapping and permafrost coring were completed in the community of Arviat (Nunavut) and comparable information assembled in Old Crow (Yukon).
- A variety of foundation adaptation options were evaluated and costed with respect to performance with the soil and ground-ice characteristics of lands slated for development.
- The decision-tree analysis was employed to identify entry points for geoscientific knowledge in the housing development process in Arviat.
- A draft report was completed on identifying economically feasible and cost-effective adaptation options for addressing landscape hazards in development of community infrastructure, with examples from Old Crow and Arviat (Bell et al. 2016).

CARRA

(Bell, Robinson, Lee, Storey, Belsheim, Whalen, Manson)

- Specific funding of the CARRA project has come to an end, but this year saw the release of the updated Sites@Risk tool for heritage managers and other to assess, manage, and maintain coastal heritage resources. A user guide for Sites@Risk was created and piloted in the Nunatsiavut Archaeology Office and published online for general use.
- Risk assessment for archaeological sites and other cultural resources along eroding coasts in the Beaufort Sea continued in collaboration with Natural Resources Canada, Parks Canada, the Inuvialuit Lands Administration, and colleagues at the Alfred Wegener Institute.

Coastal Flooding, Breakup and Erosion Hazards and Sea-Level Change

(Forbes, Atkinson, James, Whalen, Couture, Manson)

- The Mackenzie-Beaufort Breakup Newsletter was continued for the 11th year publishing at 2-3 day intervals during the 2016 breakup season (May-June) and distributed to a final mailing list of 372.
- To enhance knowledge co-production and real-time observations, a Facebook group was established under northern leadership to assess the viability of social media for dissemination of breakup status and hazard information. This attracted a membership of over 450 in a short time and functioned throughout the breakup period.
- NRCan collaborators continued monitoring coastal erosion rates in the Beaufort Sea (Yukon and Northwest Territories), with a particular focus on erosion and its impacts in the vicinity of Tuktoyaktuk.
- Following publication of an Open File report last year with tabulated projections of relative sea-level change (both positive and negative) at 57 sites in northern North America of which are 22 in the Arctic (James et al. 2015), work this year is focused on development of a tool to allow interpolation between GPS sites and provide decadal estimates of sea-level change at any location in Canada.

Coastal Climate and Weather Hazards

(Atkinson, Eerkes-Medrano, Khalilian)

- As in the previous year, three communities in the Inuvialuit Settlement Region (Sachs Harbour, Tuktoyaktuk, and Ulukhaktok) were involved in the 2016 work on adverse marine weather and conditions affecting indigenous subsistence activities on lands and waters accessed by community members.

- Participants from the three coastal communities, industry, marine transportation, and operation/ emergency response groups identified the types of activities they conduct, locations and times of the year.

RESULTS

CACCON

During the past year, the Circumpolar Arctic Coastal Communities Observatory Network (renamed the Circum-Arctic Coastal Communities KnOwledge Network - CACCON) was formally accepted as the lead activity in the Arctic Regional Engagement Network of Future Earth Coasts (www.futureearthcoasts.org) and the latter provided a substantial salary contribution (€20k) to allow us to hire a network coordinator, Michelle Slaney, based at Memorial University of Newfoundland. This greatly enhanced the communications and coordination capacity of the network. CACCON is established as a distributed network of local (community or regional) knowledge centres exchanging information, including data, technical capacity, adaptation strategies, or other types of knowledge including Indigenous Knowledge within the community or with peer communities in the circumpolar world (Figure 1). Funding limitations outside Canada continue to hamper full roll-out of CACCON internationally, although we remain engaged with pilot communities in Russia and Alaska and with partners initiating new community engagement in Greenland.

Face-to-face opportunities for sharing of local experience and strategies for solutions-oriented research have been organized over the past year in Fairbanks AK at the Arctic Science Summit Week and in St. John's NL at the Inuit Studies Conference in October 2016. During these events, local residents and knowledge leaders from seven Arctic or Subarctic coastal communities in Canada, USA, and Russia were able to exchange knowledge and approaches to enhancing local sustainability. Additional networking was facilitated by participation of northern research staff in meetings such as the Canadian Meteorological and Oceanographic Society in Fredericton (June 2016), Canadian Association of Geographers in Halifax (June 2016), and the ArcticNet Annual Science Meeting in Winnipeg (December 2016).

As noted in last year's report, the true test of CACCON is progress in the development of knowledge management and dissemination capacity at the local level. Recognizing the need to pool resources with other efforts sharing comparable goals, CACCON has partnered informally with networks such as ELOKA and A-OK (Alaska Arctic Observatory and Knowledge Hub), as well as efforts supported by the MEOPAR (Marine Environmental Observation, Prediction, and Response NCE), to promote local-level capacity building.

In several community pilots, notably in Nain and Pond Inlet, the hiring and training of dedicated staff responsible for coordinating community-based research and the generation of knowledge products available for local decision-making has proved to be a powerful enabler. In addition, the existence of an institutional framework with legitimacy within the community (e.g. Ittaq in Clyde River, NU) and physical support in the form of workspace and computer with appropriate software are critical elements. The absence of such capacity in many communities limits the potential for full community engagement and participation in research that could address specific local priorities. In some regions, such as the Inuvialuit Settlement Region, technical support established in a regional centre such as the Inuvialuit Regional Corporation and Joint Secretariat in Inuvik, can provide a level of knowledge management capacity across the region (Parrott 2016), but issues of accessibility to individual hunters at the community level remain a challenge. In other cases, external support from ELOKA and CACCON has enabled the development of local research initiatives.

SmartICE

SmartICE has been developing its sea-ice information service, culminating in demonstration projects in Nain and Pond Inlet, for the past four years (Figure 2). Working with partners and local community sea-ice experts, it has developed and refined stationary and mobile sensors that measure sea-ice thickness, generated community-scale sea-ice hazard maps from radar imagery, and discussed with communities how the knowledge produced will be managed, disseminated, shared, and integrated into a decision-making platform that serves the needs of individuals, communities and businesses. Most importantly, SmartICE is co-designed with and involves Inuit in all its operations, with the intention to integrate, not replace, Inuit Knowledge about sea-ice environments.

Cost-of-Adaptation (CAM)

The CAM activity (ongoing) addresses the following questions: (1) Given current and planned residential development in Old Crow and Arviat, which areas in these communities are vulnerable to the negative impacts of permafrost degradation and which areas are resilient? (2) What adaptations may help to alleviate the negative effects of permafrost degradation on residential infrastructure? (3) What are the economic costs of these adaptations? Which adaptations are the most (economically) feasible? How do the adaptation options fare in different geophysical zones or settings?

Results to date indicate the following: (1) As both Old Crow and Arviat are located in continuous permafrost zones, both communities are generally at risk to the negative impacts of permafrost degradation. What

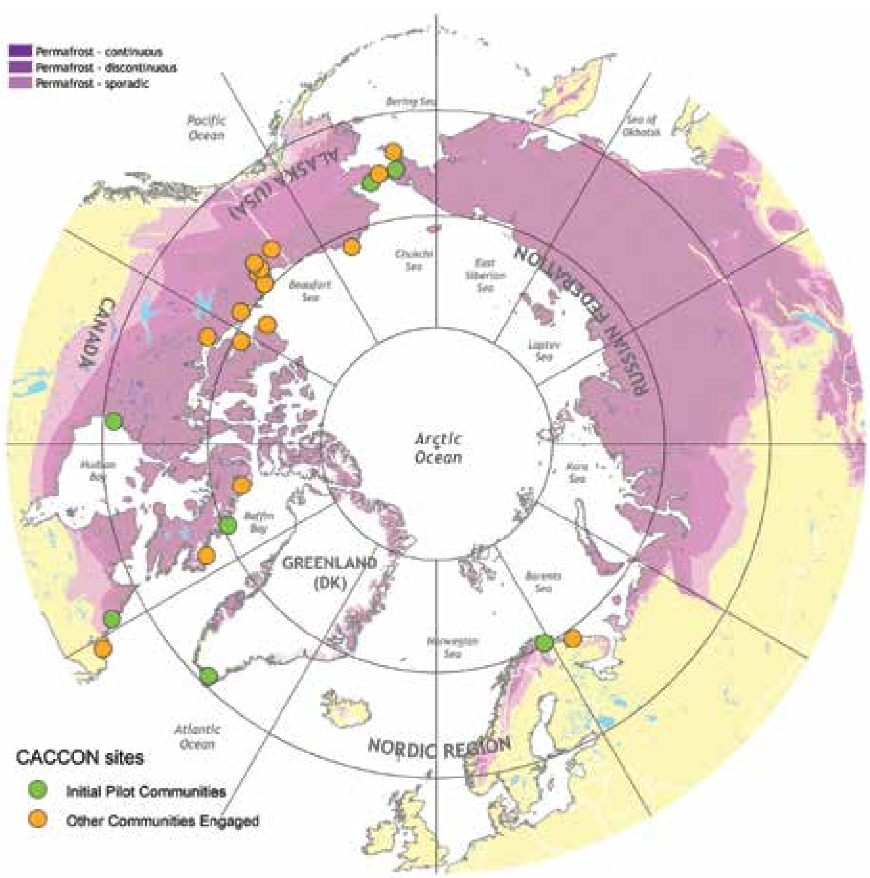

Figure 1. Distribution of CACCON pilot sites and other communities engaged with the network during the past year.

areas, then, are at relatively greater risk to permafrost degradation in Old Crow and Arviat? Based on the results of the Yukon Research Centre Hazards Mapping project for the Old Crow area, and on data provided by TetraTech EBA and fieldwork for the Arviat area, each community was divided into two zones, reflecting different levels of resilience. (2) CAM focuses on foundation-based adaptations, for the following foundation types: spaceframes, footings on permafrost, deep piles, thin gravel pads and engineered gravel pads. Thin granular fill does not perform well in any of the modeled zones. Engineered fill and footings on permafrost tend to perform better, and both have a similar level of performance. Space frames and deep foundations are found to be the best performers, with space frames performing slightly better in some cases and much better in others. (3) When foundations suffer structural defects, costs occur. Thin granular fill is the cheapest foundation option at the time of construction. But when the costs of climate change impacts are considered, it becomes the most expensive because it has poorer resistance to ground settling. Space frames are found to be the most cost-effective type of foundation, in both communities and across all zones (Figure 3). Deep foundations are the second most cost-effective option in Old Crow, while footings on permafrost are the second best option for Arviat. Further details can be found in the draft report (Bell et al. 2016).

Coastal Flooding, Breakup and Erosion Hazards and Sea-Level Change

The frequency of publication of the Mackenzie-Beaufort Breakup Newsletter was reduced this year in view of the Facebook initiative. To enhance knowledge co-production and real-time observations, an on-line group was established under northern leadership to assess the viability of social media for dissemination of breakup status and hazard information. This attracted a membership of over 450 in a short time and functioned throughout the breakup period. The forum continues mobilizing knowledge in the 'off' season through members sharing popular, media, and scientific articles of relevance, as well as fostering dialogue between members generated by inquiries and responses relating to local phenomena.

Ten coastal sites on the Beaufort Sea coast were resurveyed using drone technology by NRCan collaborators in the project (Whalen et al. 2016). Tuktoyaktuk Island, protecting the harbour behind it, is now only 50 m wide at its narrowest point and eroding at a mean rate of 2.1±0.3 m/yr (2000-2015), releasing 7773 m^3/yr of sediment which contributes to harbour shoaling (Figure 4).

Using the methods and techniques described by James et al. (2014, 2015) and reported extensively in the Government of Canada report Canada's Marine Coasts in a Changing Climate (Lemmen et al. 2016), preliminary maps of projected relative sea-level change have been produced for all coastal areas of Canada (Figure 5). The

Figure 2. SmartICE local research coordinator Andrew Arreak using SmartQAMUTIK to measure sea-ice thickness on Eclipse Sound near Pond Inlet, Nunavut (photo: SmartICE 2016).

maps are based on the IPPCC AR5 (IPCC 2013) and on crustal motions (uplift or subsidence) provided by the Canadian Geodetic Survey derived from the analysis and interpolation of the national network of Global Positioning System sites. Currently work is focused on producing projections every decade through to 2100 and developing web tools to readily access the projections for use-specified locations.

Coastal Climate and Weather Hazards

Three communities in the Inuvialuit Settlement Region (ISR) - Sachs Harbour, Tuktoyaktuk, and Ulukhaktok - participated in the 2016 work on adverse marine weather, co-supported by MEOPAR and Transport Canada. Fifteen residents (five in each community) received one-on-one training on how to access sea ice and weather information from sites such as NOAA and EC. Information results are being shared with Environment Canada so that weather forecasting can be more responsive and relevant to residents and end users in the region, in particular pertaining to focal areas of subsistence hunting and fishing activity that are often quite distant from the established settlement which weather forecasts are traditionally prepared (Figure 6). As a result of this activity, community residents and key representatives are more familiar with the range of on-line forecast services and imagery accessible to them and have also been able to share the information with a wider local audience.

PhD student Eerkes-Medrano contributed to the SEARCH-sponsored Knowledge Exchange Workshop on the Impacts of Arctic Sea-Ice Loss in Washington DC, September 2016. This advanced work towards developing a coherent source of accessible, comprehensive, and timely information that synthesizes the connections between the science of Arctic sea ice loss, key societal issues, and stakeholder needs. Additional MSc, work developed a climatology of low visibility events by weather type for the ISR communities of Sachs Harbour, Ulukhaktok, Tuktoyaktuk, Inuvik and Aklavik.

DISCUSSION

The CACCON approach has attracted wide interest in the Arctic community as well as inquiries about its applicability in regions beyond the Arctic. The 2016 White Paper (Forbes et al. 2016) has influenced thinking in working groups of the Arctic Council, in Future Earth, and in MEOPAR, another Canadian NCE. At the annual meeting of Future Earth in Bern, Switzerland, in June 2016, a presentation by Martin Le Tissier, Executive Officer of Future Earth Coasts, attracted wide attention and put CACCON on the global sustainability science map. Project NIs and students were invited to present at the first Arctic-COAST workshop in Murmansk in June 2016:

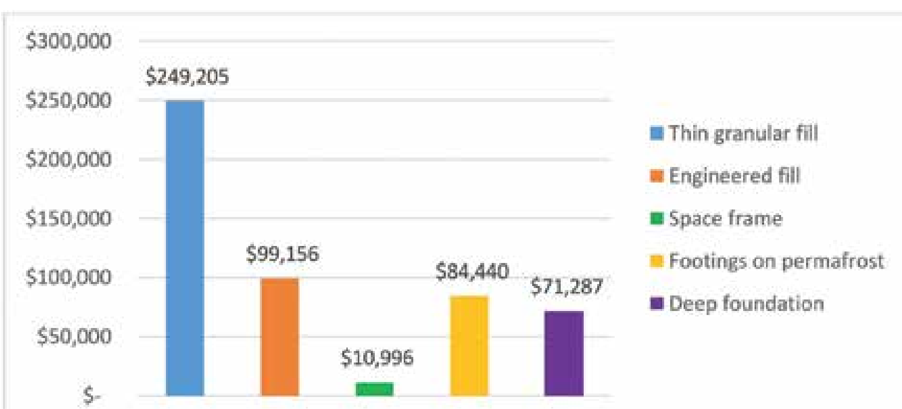

Figure 3. Expected (discounted) lifetime costs of climate change for housing built on different types of foundation (average cost per house) (from Bell et al. 2016, submitted). © 2016 Bell, Dion, Kors-Olthof, Perrin, Riedlsperger, Trimble.

Indicators, Resilience and Governance in Arctic Coastal Social-Ecological Systems. In a keynote address, NI Forbes "emphasized the need to foster peer-to-peer networking among Arctic coastal communities through capacity sharing [and] co-learning [for] sustainability" (Riedlsperger 2016). Northern residents with a rich store of Indigenous Knowledge and a culture of adaptation can enrich and benefit from CACCON as a pan-Arctic network of communities and knowledge hubs that promotes collaboration to advance adaptation planning.

Despite many initiatives such as community-based monitoring (e.g. Johnson et al. 2015), locally directed research (e.g. Gearheard et al. 2006, 2011; Pulsifer et al. 2012), and northern approaches to sustainability (Riedlsperger et al. 2017), capacity for co-production and mobilization of knowledge to support goals of sustainable development remains limited in most places. Even at regional scales, some territorial government agencies and regional indigenous organizations and governments host substantial technical expertise, but require specialized scientific partnerships to address priority issues, including environmental challenges such as coastal erosion, flood risk, navigation support (harbour development), permafrost degradation affecting provision of safe and adequate housing, and major development projects (hydrocarbon exploration, mine development, reservoir construction).

Figure 4. Frozen cliff face of Tuktoyaktuk Island in April 2016, with snow ramp mostly covering a multi-metre deep undercut cliff-base niche, which formed in a storm just before freeze-up the previous fall (photo: Laura Eerkes-Medrano).

Documentation of the evolution of solutions-oriented research in Nunatsiavut over the past 10 years has been instructive (Bell 2016; Riedlsperger et al. 2017). Beginning with the land claim settlement in 2005 and a community visioning exercise (the Tukisinnik Community Research Forum in June 2010), Labrador Inuit "reclaimed the research agenda for their communities and their homeland" (Bell 2016). Out of this grew a community consensus that research could be designed to address local knowledge gaps and priorities. This evolved into the SakKijânginnatuk Nunalik (Sustainable Communities) Initiative, which focused on housing condition as a top priority and a driver of many other challenging issues in Nunatsiavut communities. The resulting knowledge-to-action plan, SakKijânginnatuk Nunalik: an integrated action plan for healthy homes in thriving Nunatsiavut communities, was awarded a share in the 2013 Arctic Inspiration Prize. The insights derived from this work informed both a food security and youth health adaptation project, Going Off, Going Strong, and (in response to rising concerns about thin ice) the origins of SmartICE.

The emergence of SmartICE as a widely known project and primary exemplar of CACCON has attracted wide interest in the media (e.g. Lunau 2016; Zelniker 2016; Harron 2016) and inquiries from other communities where similar concerns about changing ice conditions abound and the need is just as great as in the pilot communities. CACCON communities and others throughout Inuit Nunangat and as far afield as Chukotka have expressed interest in replicating SmartICE in their regions.

While the pilot projects in Nunatsiavut and Pond Inlet have been eminently successful, integrating digital satellite, *in situ*, and mobile sensor data with Inuit ways of knowing and understanding of sea ice, the prospects for sustaining the effort in these pilot communities or expanding to a wider network are uncertain and dependent on continued grant support. For this reason, a new approach has been conceived to support the SmartICE objectives while promoting northern technical training and economic development

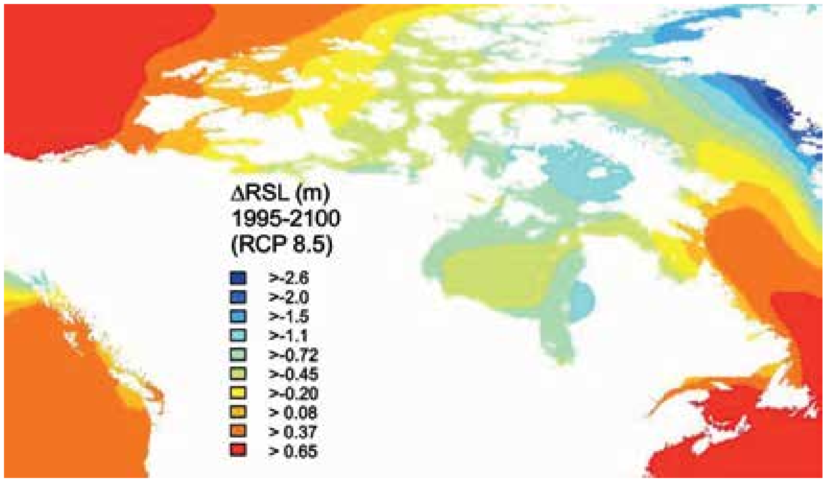

Figure 5. Projected relative sea-level change across Canada at 2100 (relative to 1995) for a high-emissions scenario (RCP8.5).

capacity and creating a model for sustainability. The proposal is to establish a northern social enterprise, SmartICE Inc., to support community ice awareness knowledge products through the manufacturing of sensors by youth at risk in a northern community, the development of a data management centre in the north, and funding of the enterprise through the sale of sensor equipment to other communities and of data products to industry or other institutions. For this vision, SmartICE Inc. shared in the 2016 Arctic Inspiration Prize.

The housing crisis identified and addressed in Nunatsiavut is a widespread phenomenon across the Arctic, providing a context of some urgency for the CAM project. While still in progress, CAM confirms the hypothesis that housing in Arviat NU and Old Crow YT is and will continue to be affected by the impacts of climate change, leading to higher costs at various levels of government. In part, these costs occur because housing foundations will require more maintenance and repair, and will become more likely to suffer structural damage affecting habitability. Thus there may be costs accruing that stem from the negative impacts of inadequate housing on residents.

CAM shows that adaptation options can be implemented to reduce some of the negative impacts of climate change on housing. Importantly, when these impacts are considered, some foundations are less resilient than others. In the case of Arviat and Old Crow, space frame foundations are the best performing, and offer the best value for money. Notwithstanding adaptations, there is a cost of climate change adaptation for the housing sector in both communities. In each community, the cost difference between space frames and the cheapest alternative option is the cost of adapting to the expected impacts of climate change on housing. It is approximately $10,000 per unit in Old Crow and $15,000 in Arviat. CAM provides an argument for decision-makers to show not only that adaptation options are available, but that they are economically sensible even, or especially, given limited financial resources.

Coastal erosion is a grave concern in the ISR, where it is leading to rapid loss of archaeological and cultural resources and threatening community and subsistence infrastructure (Lamoureux et al. 2015; Fritz et al. 2017). There is growing evidence for an acceleration in the rate of coastal retreat and Tuktoyaktuk Island is at risk of breaching within 20-25 years, with serious implications for the viability of Tuktoyaktuk Harbour. NIs and collaborators in the project spent time in the community and in discussion with Inuvialuit, hamlet, and territorial officials about shore-protection options.

Figure 6. Knowledge co-production in Tuktoyaktuk with PhD student Laura Eerkes-Medrano and resident hunter/ knowledge holder (photo: CACCON 2016).

CONCLUSION

The overarching goal of this project is to enhance community well-being by making appropriate knowledge available for decision-making. This knowledge can come from community members (IQ or other information from the community) or can be produced by or with research partners. The key ingredient is the ability to access and manage information that will help to make decisions that make a difference in the lives and well-being of community members and move the community toward a more sustainable future. Addressing the many complex and inter-related issues facing Arctic coastal communities requires a holistic approach, consistent with Inuit ways of knowing, and a combination of different types of knowledge, values and perspectives from multiple disciplines. Through connecting community knowledge centres, academic researchers, and indigenous organizations and governments that host substantial technical expertise, the Circum-Arctic Coastal Communities KnOwledge Network (CACCON) can build bridges to make relevant knowledge more accessible, and support solution-oriented knowledge co-production by facilitating peer-to-peer communication and knowledge-sharing with partner centres around the Arctic. Specifically, the project will support key components of ongoing and future observing, change detection, and scenario testing functions, to address a broad range of challenges. Through combining local indigenous knowledge and practice with scientific information and state of the art technology, the project has made advances in information needs for transportation, built infrastructure, healthy homes, preservation of culturally important sites, safe sea-ice travel, food security, the costs and benefits of adaptation options for housing, and requirements for contaminant prevention and mitigation in support of health priorities in northern coastal communities.

ACKNOWLEDGEMENTS

This project benefits from the efforts and engagement of a long list of northern residents, community research champions, academic and government partners, international colleagues, and governance institutions at municipal, regional, territorial, and federal levels. We are particularly indebted to past and present ArcticNet students who have contributed to this and preceding projects. It is a pleasure to acknowledge the financial support of ArcticNet and NCE Canada to enable this work to go forward. Financial and in-kind support has also come from numerous other institutions and agencies, which are acknowledged specifically in the reports and papers arising from the project.

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ENHANCING COMMUNITY-BASED ENVIRONMENTAL MONITORING IN THE CANADIAN ARCTIC FOR LOCAL AND REGIONAL ASSESSMENTS AND ADAPTATION STRATEGIES

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The ethnobotany and medicinal properties of Rhodiola rosea in Nunatsiavut and potential applications in community-based nutraceutical marketing enterprises
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Linking science and traditional knowledge through ecology of berry producing shrubs in the Kugluktuk region
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ABSTRACT

The Arctic is experiencing rapid environmental change, and communities are seeing and feeling the changes directly. Climate warming is resulting in thawing permafrost and unstable land, affecting community and industrial infrastructure. The warming is also increasing the growth of shrubs and changing the vegetation, which in turn will affect smaller plant species, such as berry plants and lichens, and affect important wildlife species, such as caribou. In addition, landscape disturbances, such as thaw slumps and fires, are becoming more frequent and larger, affecting travel routes and the land and water systems. Besides these natural disturbances, industrial impacts are increasing as the pace of development accelerates in many areas of the Canadian Arctic. In order to better cope with and adapt to the changes in their environment, Inuit and other northerners need a wide range of information that is relevant to their local and regional circumstances. Scientific research and monitoring provide important sources of information for understanding the impacts and consequences of the environmental changes. However, land users in communities across the Arctic have the unique perspectives of being on the land, noting the changes in the context of their sophisticated understanding of their environment. In our project, we will conduct studies to bring together both scientific and community-based monitoring of the environmental changes that is relevant to communities. We will use a combination of interviews, mapping, remote sensing and plot level studies to provide the diverse information needed to understand and adapt to the changing environment. We will introduce a new web-based interactive mapping platform (the Community Knowledge Keeper) to help communities catalogue and store traditional knowledge and indigenous information on environmental change. We will also work with high school science classes in each of the communities to train students in measurement techniques for environmental monitoring. They will also learn to interview elders to gain Inuit perspectives on how the environment is changing and how to adapt. We will also continue to collaborate with Nunavut Arctic College Environmental Technology Program in Iqaluit, by introducing new monitoring protocols and participatory multimedia mapping. Ultimately, we hope to see a network of sustained community-based environmental monitoring across the Canadian Arctic that contributes needed information for communities, scientists and governments.

KEY MESSAGES

- Berry productivity is highly variable in space and time among the common berry species across the Canadian Arctic and but is highest in open habitats in bioclimatic subzone D than in higher latitudes or in forested sites.
- Our experimental studies and long-term observations show that berry production is lowest in sites where tall shrub species respond strongly to warming or fertilization, indicating a potential decrease in berry productivity as tundra systems respond to climate change.
- Very little of the total production of berries is consumed by animal herbivores, including birds and small mammals. Only 2% of berry productivity was consumed by animal herbivores (mainly snow geese) in a study of berry productivity near Arviat.
- Wet sedge tundra ecosystems in the Torngat Mountains, Labrador are drying out resulting in significant changes in vegetation.
- Ecosystems across the Inuvialuit Settlement Region are undergoing rapid transformations in response to climate change and altered disturbance regimes. Cover of shrubs has increased in most terrain types, and the cover of lichens has decreased.
- Ice-rich till deposits on Banks Island have the highest density of permafrost disturbances in the Canadian Arctic.

- Traditional knowledge of berry ecology is useful in encouraging Inuit youth to learn Inuktitut and IQ from elders. In Kugluktuk, the production of "The Berry Book" showed that this was a productive avenue for engaging youth with Innuaqtun and their elders.
- The community-based monitoring of the George River water quality in Kangiqsualujjuaq, Nunavik, through a Science Land Camp is a good example of a coordinated, collaborative and interdisciplinary approach answering a local environmental concern.
- The Avativut Mobile teacher training sessions showed that Avativut Learning and Evaluation Situation (LES) were among the students' preferred ones and that Inuit teachers showed a great interest in these activities.
- Growth and phytochemistry of Roseroot (*Rhodiola rosea*) vary across sites according to latitude and substrate, with growth higher in female plants. This information can be used to help determine the best sites to harvest Roseroot and to choose populations for cultivation for a new natural products business in Nunatsiavut.

OBJECTIVES

The overarching objective of our research is to enhance local environmental monitoring across the Canadian Arctic such that the programs are self-sustaining and become important sources of information for local and regional assessments of change and facilitate planning and the development of policy for adaptation and resilience. We build on our successful community-based research focussed on berry production and vegetation change in Nunavut, Nunavik and Nunatsiavut, and expanded the research into the Inuvialuit Settlement Region (ISR). Ultimately, we wish to facilitate the long-term stewardship of this knowledge base in each region and provide a lasting legacy of ArcticNet.

The project has three general objectives for research with and near communities:

1. Enhance existing community-based berry production and vegetation monitoring in Canadian Arctic communities.
2. Conduct environmental monitoring of importance to communities.
3. Strengthen involvement of Inuit youth in environmental monitoring using science and Inuit knowledge.

KNOWLEDGE MOBILIZATION

- Nine presentations at conferences
- 10 interviews with media
- Mentoring of eight northern research partners
- Published book of interviews from eight communities: "The Caribou Taste Different Now" was widely reported in northern media, and was recommended on the CBC Holiday book list in December, 2016.
- Published book of traditional berry knowledge and recipes for the Kugluktuk region (The Berry Book) in Innuaqtun and English. The school will use the book in their Innuaqtun classes.
- Completed and provided posters for each of eight communities based on interviews completed in those communities.
- Visited three northern communities to present results and discuss next steps as ArcticNet draws to a close.
- Published seven academic papers, including the first long-term study of berry productivity in Finland.

INTRODUCTION

The rapidly changing climate and increasing disturbance (natural and human-caused) are driving ecological change across the Canadian Arctic (Gérin-Lajoie et al. 2016; Henry et al. 2012; IPCC 2014). Recent changes include shifts in the frequency and magnitude of natural disturbances, changes in the timing of formation and melt of sea and lake ice, permafrost degradation and decreasing land stability, changes to vegetation structure, shifts in animal population size and distribution, and changing water quality and quantity (e.g. Elmendorf et al. 2012; Kokelj et al. 2013; Lantz et al. 2009; Segal et al. 2016; Sturm et al. 2005). These environmental changes have impacts at local and regional scales, including potential positive feedbacks to climate warming through vegetation change and altered energy and carbon fluxes (Chapin et al. 2005; Elberling et al. 2013). They also impact northern indigenous communities whose livelihoods and well-being are linked to the health of the land (Gérin-Lajoie et al. 2016; Krupnik & Jolly 2002; Parlee et al. 2005). Impacts can be direct (e.g. loss of travel route) or indirect (e.g. changes in vegetation and cascading effects on culturally important foods, such as berries). In order for northern communities, researchers, and decision makers to manage and adapt to changing environmental conditions, diverse information about the location, extent, and drivers of local and regional changes is needed (Pearce et al. 2009). Many Inuvialuit and Inuit land users are in a unique position to monitor local environmental conditions and detect changes because they spend a large portion of the year on the land and have a sophisticated understanding of historical environmental variation. The number of research programs in the Canadian Arctic that have incorporated Inuit and Inuvialuit knowledge (IK) has grown considerably over the past 20 years, and IK was an essential component International Polar Year program (Grimwod et al. 2012; Henry et al. 2012). However, despite ongoing interest in environmental research that integrates local knowledge, significant challenges remain in implementing programs consistent with community needs that will provide the long-term data sets required by environmental scientists, regional planners and regulators (Bonny and Berkes 2008; Brunet et al. 2014). Our ArcticNet project aims to enhance the integration of environmental research and monitoring with local knowledge and to provide a lasting legacy for Arctic communities to build on.

ACTIVITIES

Fieldwork was conducted across the Arctic throughout the summer of 2016 and included measurements of berry production and vegetation change near communities and at long-term research sites. Community based monitoring and research activities continued in all regions of the Canadian Arctic.

Tundra plant ecology, berry productivity and environmental change

- Berry productivity measurements were made in long-term plots at the three research stations: Alexandra Fiord, Bylot Island, and Daring Lake, and at Pond Inlet, Iqaluit, Nain and Saglek. This is the 9th year for annual measurements of berry productivity as part of our ArcticNet project.
- Vegetation composition and abundance was measured in warming experiments at Alexandra Fiord, Nain, and Saglek (Torngat Mountain National Park), and in long-term monitoring plots at Bylot Island. The vegetation changes in the ontrol plots of the experiments are consistent with the earlier changes observed in the warmed plots.
- Impact of increased shrub cover continued to be studied in an experiment with shrub growth increased by fertilization near Umiujaq, Nunavik.
- Phenology of wetland plants near Umiujaq continue to be studied using time-lapse photography. This project is linked to the project SAuVER, a network of phenology sites across Quebec.

- Photographic methods were used to assess seasonal phenological changes in vegetation in plots at Alexandra Fiord, which show changes the green-up and senescence related to experimental warming and tundra plant community type.

Community-based environmental monitoring

- A science land camp was organized and held with the community of Kangiqsualujjuaq, based on measuring water quality in the George River.
- Development of the berry and vegetation monitoring project (Learning and Evaluation Situation (LES)) of the Avativut Program continued to be improved in anticipation of the continuation of the program with the Kativik School Board in Nunavik. The Berry LES received comments from participants and these are being used to improve the program.
- All Avativut berry data since 2012 were compiled and validated. Summary tables of berry productivity (g/m^2) were produced.
- A graphing tool was developed from the berry database summary tables from the Avativut Berry LES to produce automated graphs. Historic climate data (1980-2010) from Environment Canada for the nearest weather station (mean normal July temperatures and precipitations) were used to link berry productivity to climate.

Education and Outreach

- The book based on our interviews with elders and other knowledge holders in eight communities across Nunavut, Nunavik and Nunatsiavut during 2007-2010 (The Caribou Taste Different Now, Inuit Elders Observe Climate Change) was published and released by Nunavut Arctic College Media in May 2016 (Gérin-Lajoie et al. 2016).
- A book describing the observations of elders in Kugluktuk of changes in berry production, as well as stories about and recipes involving berries (The Berry Book) was published in October 2016 (Kugluktukmiut Elders & Youth and Desrosiers 2016). The book is in Innuaqtun and English.
- Teacher training workshops for the Avativut Program were held in Inukjuak and Umiujaq in March 2016, with support from both ArcticNet and Ouranos.
- An open house was hosted at the Nain Research Centre to present and discuss results from studies conducted in the region over the past five years, including the book The Caribou Taste Different Now.
- A regional assessment of Indigenous observations of environmental change in Nunavik, Nunatsiavut and Naskapi regions was completed.
- Our group participated in the Science Fair at the Qarmartalik school in Resolute, and talked with students about our research.

Natural health products: Rhodiola rosea

- Graduate thesis based on initial studies and economic analyses for a natural products business in Nunatsiavut nearing completion, and will be used to develop a full business plan for the government of Nunatsiavut.
- A meeting with the Finance minister of Nunatsiavut was held in September 2016 at the Inuit Studies Conference in St. John's, and she requested an executive business summary to evaluate the project for possible financial support.
- Initial contacts with community members and agencies in Nain, Hopedale and Postville showed very strong interest in the project.

Syntheses and Database Activities

- Analyses of the berry productivity data collected from all research sites and communities over the past nine years continued, with a plan to submit a manuscript describing the study in summer 2017.
- Plant phenology data from our studies were used in a global synthesis of tundra phenology

published in Global Change Biology in January 2017 (Prévey et al. 2017).

- Discussions continued on how best to ensure the continued use and development of the data related to our project. Platforms investigated last year did not seem appropriate or user-friendly for community members. This is an important issue for our project: ensure the legacy of information can be used and enhanced by the communities.

RESULTS

Our studies continued in communities and research sites across the Canadian Arctic in all areas related to our original objectives. Results are published in two new books, which describe changes observed by community elders, and in journal articles, and have been presented in meetings throughout the past year. We also continued to work with communities, schools and school boards to use our results to enrich the curriculum of high school science classes, and to train teachers in field based course modules. In addition, our project examining the potential for creating a natural products business in Nunatsiavut. We are pleased that our research is truly interdisciplinary, and involves science, local knowledge, education and business.

Tundra plant ecology, berry productivity and environmental change

Analyses of berry productivity from 12 sites established since 2008 (Figure 1) are now complete and form the first such data set in Canada. Berry production of the three focal species (*Empetrum nigrum*, *Vaccinium uliginosum*, *V. vitis-ideae*) was greatest in sites found in bioclimatic subzone D, including Pangnirtung, Iqaluit and Kangiqsujuaq (Figure 2). The most northern sites had the lowest productivity, and only *V. uliginosum* was found at these sites. However, the greatest production was not found in the warmest sites in subzone E.

In the only study of its kind, berry production across the various landscape types in a 45.5 km^2 area in the vicinity of Arviat, Nunavut was estimated as 463.9 kg, 21.4 kg, 11.7 kg, 8.8 kg and 4.8 kg, respectively, for *Empetrum nigrum, Vaccinium vitis-idaea, Arctous alpina, V. uliginosum* and *Rubus chamaemorus* (Boulanger-Lapointe et al., in prep.). Measurements of the use of berries in the area by geese, lemmings, and other herbivores showed only geese were important consumers of berries, but only ate ca. 2.4% of the total production.

Berry production at the site level is affected by a suite of biological and physical factors. Lower production was found in all three focal species at the long-term monitoring site near Nain, Nunatsiavut in areas with tall shrub cover (Figure 3). Productivity of *E. nigrum* was high in dry sites, and both species of *Vaccinium* had greater production in warmer soils.

Experimental warming studies at Nain and Saglek showed that the control plots were also changing in the same direction as the warmed plots (Figure 4). There was significant increases in shrub cover at both sites, but especially in Saglek where dwarf birch (*Betula glandulosa*) as increased dramatically since 2009 (Figure 5). The large increases in shrub cover at Saglek occurred with decreases in lower growing plant forms, including forbs, graminoids and moss.

Long-term warming experiments at Alexandra Fiord showed significant increases in annual growth has occurred in the evergreen dwarf shrub in both warmed and control plots over the past 25 years (Figure 6), and that the growth is further stimulated in the warmed plots.

In wetland communities at Umiujaq, plant community phenology monitored with automatic time-lapse cameras show the full period of greening to senescence (Figure 7). The length of the season the photosynthetically active season length was determined by calculating a greenness index from the images (Figure 8), which showed the average length of the photosynthetic season was approximately 80 days over the three seasons.

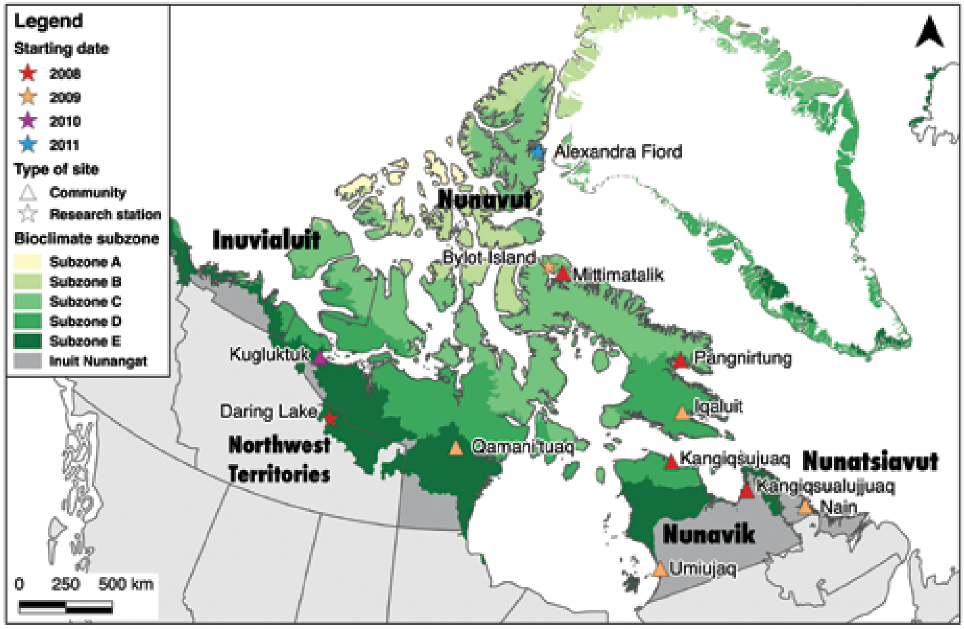

Figure 1. Location of berry monitoring sites across the Canadian Arctic, showing the date of establishment of the berry plots and the bioclimatic subzones according to the Circumpolar Arctic Vegetation Map (Walker et al. 2005). © 2009, John Wiley and Sons. © 2005 IAVS - the International Association of Vegetation Science.

Community-based environmental monitoring

Berry production and vegetation monitoring was conducted in fewer communities this past year, due to circumstances at the Kativik School Board (KSB) in Nunavik. The Berry Monitoring LES (and the Permafrost LES) in the Avativut Program were not implemented this year as the KSB was reviewing parts of the curriculum. However, berry production and vegetation measurements were conducted at Nain, Iqaluit and Pond Inlet.

A Science Land Camp was held in Kangiqsualujjuaq, which is co-leading the effort for the land camp. The camp was focussed on measurements of water quality of the George River, given the community's concerns about planned mining activity in the upper parts of the watershed. Figure 9 shows the fieldwork activities by youth from Kangiqsualujjuaq on the shore of the river.

Planned community-based activities at Sachs Harbour were also postponed until next year due to logistical problems. Temperature and other sensors were

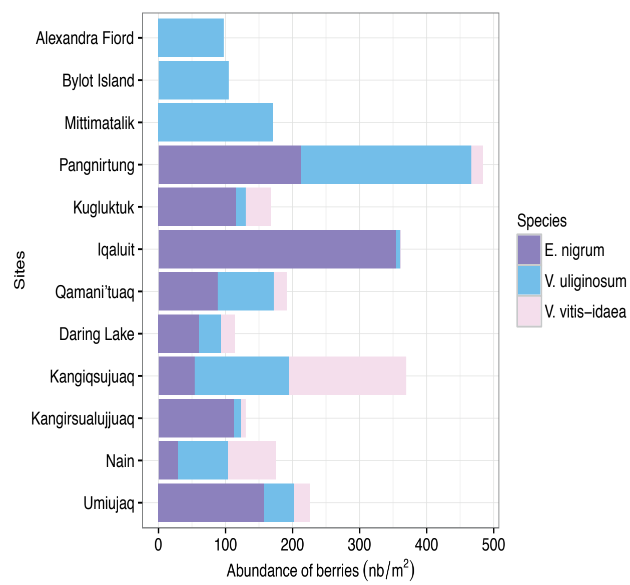

Figure 2. Mean abundance of berries (#/m^2) measured at 12 sites across the Canadian Arctic. Data are based on annual harvests at each site, and sites are arranged in latitudinal order from south to north.

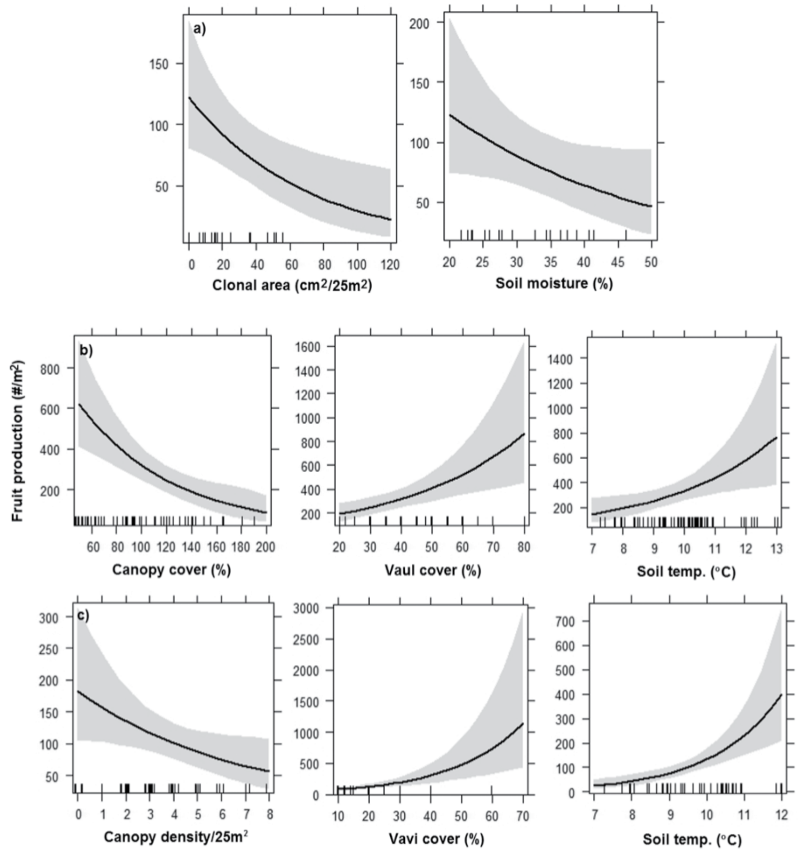

Figure 3. Effects plots from generalized linear regression (negative binomial error, log link) indicating the magnitude and strength of significant parameter effects of variety of biotic and abiotic factors on fruit production (total # fruits and owers/m²) in a) Empetrum nigrum, b) Vaccinium uliginosum (Vaul) and c) Vaccinium vitis-idaea (Vavi). Shaded areas represent 95% confidence intervals.

established last year near the community to monitor changes in permafrost features, and these will be recovered next summer. Contacts in the community are continuing to check the sites.

Education and Outreach

Avativut Program

The KSB has said the Avativut LES are in line with their orientation to make the curriculum more culturally relevant and expect the program will re-start in 2017-18. We will continue to support teachers with the activities in 2017-2018. In fact, Teacher training workshops for the Avativut Program (Avativut Mobile) were held in Inukjuak and Umiujaq in March 2016, with support from both ArcticNet and Ouranos.

A graphing tool was developed from the berry database summary tables in the Avativut program to produce automated graphs. Historic climate data (1980-2010) from Environment Canada for the nearest weather station (mean normal July temperatures and precipitations) were used to link berry productivity to climate. Queries can be made by village, species or year (Figure 10). This type of application will also be useful to illustrate other

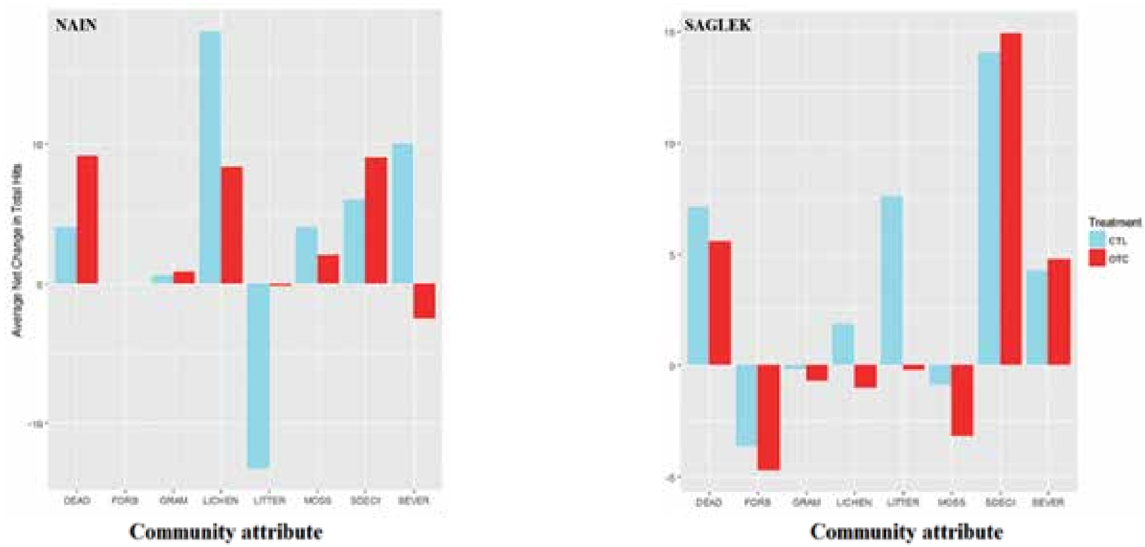

Figure 4. Barplot indicating average net change in total number of point frame hits for all community attributes between 2009 and 2016 in Nain and Saglek warming experiments. CTL = control plots and OTC = plots with open top warming chambers: Nain n= 18; Saglek n=58.

datasets, for example ice onset and breakup dates, ice thickness or active layer thickness.

Outreach posters were created in collaboration with a graphic designer to visually explain the Avativut Program's general objectives, values and philosophy (Figure 11). The posters will be sent with the Berry overall result poster in all Nunavik schools before the end of March 2017.

The book The Caribou Taste Different Now: Inuit Elders Observe Climate Change, based on multiple interviews conducted by our group between 2007 and 2010 in eight communities in Nunavut, Nunavik and Nunatsiavut, was published by Nunavut Arctic College Media in June 2016. The first version of the book was released in Baffin Inuktitut (syllabics) and English, and other versions for Nunavik (Nunavik Inuktitut (syllabics) and French) and Nunatsiavut (Nunatsiavut Inuktitut (roman orthography) and English) are in preparation. It drew media attention and was on the CBC Holiday Gift Guide Selection http://www.cbc.ca/books/holidaygiftguide2016/, a review was made in Nunavut News and two radio interviews were also broadcasted. In addition, a review in the journal Arctic is forthcoming.

The results presented in the book show there were interesting differences among the communities, but there was a consensus that temperatures were increasing in all seasons of the year, there were changes in snow and ice cover consistent with the changing climate, and there were noticeable changes in vegetation with increases in shrubs, and in trees in the most southern communities. Differences were noted in the changes in precipitation, with more precipitation

Figure 5. Photograph of OTC overgrown with dwarf birch (Betula glandulosa) in Torr Valley, Saglek, Labrador.

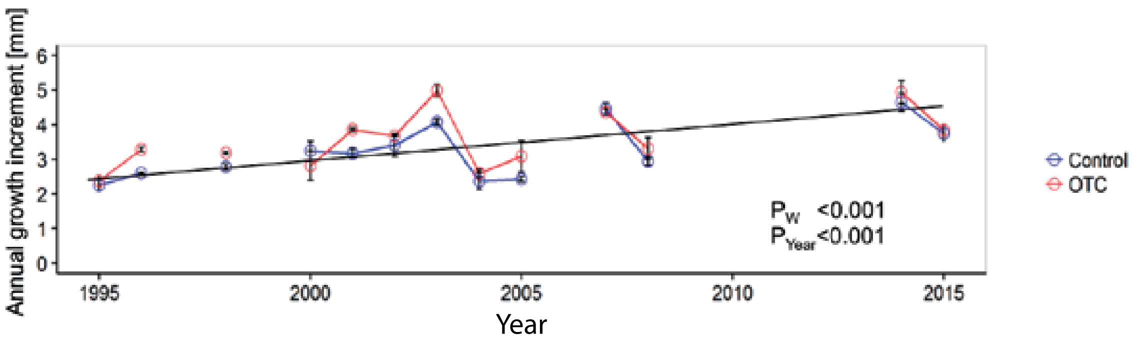

Figure 6. Annual growth increment in the evergreen dwarf shrub Cassiope tetragona L. in experimentally warmed and control plots at Alexandra Fiord, Ellesmere Island, Nunavut. The trend line is estimated to show direction. Measurements not made each year: n = 12. (Frei and Henry, in prep.).

reported in the eastern communities (e.g. Nain) and a decrease reported in the western communities (Baker Lake, Kugluktuk).

A book specific to studies conducted in Kugluktuk was also published this past year. "The Berry Book" describes the studies of berry productivity and use in the community conducted with the high school science classes during 2012 and 2013. It includes results of interviews conducted by students with elders regarding environmental changes, but focussed on changes in berry shrubs. The students used the opportunity to learn about berry ecology and uses, as well as stories related to berries from their elders. They were also encouraged use the opportunity to learn Innuaqtun terms for berry plants and environmental variables. Stories and observations about the changes in each of the five berry species were recorded and, as in other communities, there was concern that the berry plants were being affected by increases in shrubs. In some cases, elders noted that they did not taste the same now.

Natural health products: Rhodiola rosea

Roseroot (*Rhodiola rosea*) is being studied in Nunatsiavut to both conserve the local populations and to determine whether a local natural health products business could be built based on cultivation of the plant. As part of the study, growth and phytochemistry of different populations was studied to assess which environmental variables are important. A multivariate analysis of growth variables (height, fruit weight, numbers of ramets and leaves) indicated that the sex of the plant, latitude of the site, and substrate type were important in distinguishing among the populations (Figure 12). Female plants tended to have higher growth rates, as did the southern populations. The analysis of the leaf phytochemistry of the populations also showed they could be separated by latitude (southern populations had higher concentrations) and substrate type (Figure 13). Interestingly, neither growth nor phytochemistry were affected by the level of weevil infestation that affects the *Rhodiola* populations in Nunatsiavut.

Figure 7. Wetland site new Umiujaq monitored for phenology using time-lapse cameras. Some of the camera stations can be seen in the photo.

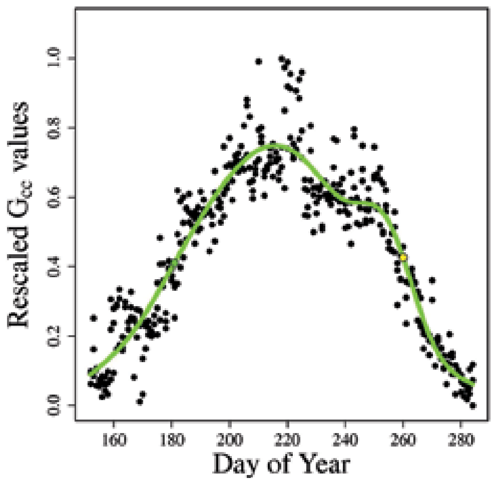

Figure 8. Determination of the length of the photosynthetically active season based on the Green chromatic coordinate index (Gcc) calculated from the images. The start of the season is shown by the green dot and the end by the yellow dot.

Figure 9. Photograph of youth from Kangiqsualujjuaq on the shore of George River performing water quality analyses as part of a Science Land Camp in July 2016. Photo by J. Lajoie-Gérin.

Syntheses and Database Activities

As mentioned, a synthesis of all berry productivity data from communities and research sites involved in our ArcticNet research since 2008 is underway and results show expected variability along the latitudinal gradient, but maximum productivity occurs in Low Arctic areas (bioclimatic subzone D), not in sites with higher temperatures in the forest-tundra (subzone E) (Figure 2).

A regional synthesis of observations by members in three Eastern Subarctic communities showed agreement on warmer winter temperatures, decreasing quality of snow, freeze-up is later and precipitation patterns are different. The observations were analyzed with regional climate data. The synthesis was based on methods developed our project and has been accepted for publication in Regional Climatic Change (Rapinski et al. 2017).

As our project comes to a close next year, we are actively seeking methods to archive the data but make them available and useful to the communities that have been involved, and who will likely continue the monitoring we have established. The data will also be useful to future researchers. After meetings at the ASM in Winnipeg and in subsequent phone conferences, we have decided to use an easily accessible platform on Google, which has been successfully used by anthropologists at the University of Victoria.

DISCUSSION

Tundra plant ecology, berry productivity and environmental change

All of our studies on berry productivity, vegetation, permafrost disturbance, using both scientific approaches and traditional knowledge show that the Canadian Arctic is changing rapidly in response to human-induced climate change. Inuit observations show variability in the changes in the vicinity of communities, in relation to their location and typical weather patterns, but all participants noted increases in temperature, changes in precipitation patterns and snow conditions, and increases in shrub cover (Gérin-Lajoie et al. 2016). These observations are backed by the results from our scientific studies, showing advances in phenology of tundra plants (Prévey et al. 2017) and increases in shrub cover in both experimentally warmed and control plots (Elmendorf et al. 2012a, 2012b; Fraser et al. 2014; Moffat et al. 2016). In addition, warming in the Inuvialuit region is resulting in significant increases in permafrost disturbances, especially in ice-rich permafrost regions (Segal et al. 2016). These unprecedented changes in the Canadian Arctic are causing concern in Inuit communities, and add to the every growing evidence of the need to find solutions and adaptive strategies at all scales.

Berry picking is a treasured activity in the communities for both the cultural and food values, but increasing shrub cover appears to be causing lower berry shrub presence and productivity. Inuit observations also report these changes (Kugluktukmiut Elders & Youth and Desrosiers 2016; Gérin-Lajoie et al. 2016). This is concerning for the future of some traditional areas used for berry picking, especially in communities in bioclimatic subzone E, where tree and tall shrub cover are increasing rapidly (Elmendorf et al. 2012b; Gérin-Lajoie et al. 2016; Myers-Smith et al. 2011). The production of berries is considerable, especially in tundra near communities in the Low Arctic bioclimatic subzone D (Walker et al. 2005). The consumption of berries by humans or herbivores, such as snow geese does not affect production in the southern regions (subzones D and E). This in contrast to berry production by Bilberry (*Vaccinium myrtillis*) in Europe, which has been shown to be negatively affected by mammal and moth herbivory (Boulanger-Lapointe et al. 2017).

Community-based environmental monitoring

In their evaluation of the curriculum, the Kativik School Board decided the Avativut program would not be run in the schools of Nunavik for 2016. They expect to re-establish the program in the coming year, as the KSB indicated they value the program. One of the mechanisms to increase the success of the program is the teacher training workshops, which worked very well last year, and will be run again this year. Monitoring did take place in Nain, Iqaluit, and Pond Inlet, as well as at research stations. The Berry LES (as well as the others in Avativut) is being restructured to based on comments from the communities about the usefulness of the program. This will make the program more relevant to community needs.

Monitoring of the vegetation and berry plots near Iqaluit was again completed by the students in the Nunavut Arctic College Environmental Technology Program. This training will help improve capacity in some communities to continue the monitoring beyond the end of ArcticNet.

Education and Outreach

The Avativut Mobile teacher training workshops helped the participants to better understand the scientific protocols and prepare for the activities, to be more confident in bringing their students on the land and to realize the importance of data entry. It also fostered more collaboration between the non Inuit and the Inuit teachers. From these training sessions, we learned that Avativut LES are among the students' preferred ones and that Inuit teachers, especially, are showing a great interest in these activities. Some participants recommended improvements to the interview kit, to produce more graphs from data and to develop tools for data entry and analysis (e.g. games).

The Avativut team has been solicited to adapt the educational material and activities for other groups, indigenous and non indigenous. We will adapt the Berry LES to the Atikamekw Nation. In addition, the Commission scolaire du Littoral on the Lower North Shore in Quebec has expressed interest in starting a pilot project in some communities with Berry and Ice monitoring, combined with LTEK collection with local inhabitants. Hence, the success of our education and outreach components is being noticed, and our methods are being adapted to new situations outside of the Arctic.

Our most important outreach products this past year were the publication of two books based on interviews with community members in eight communities

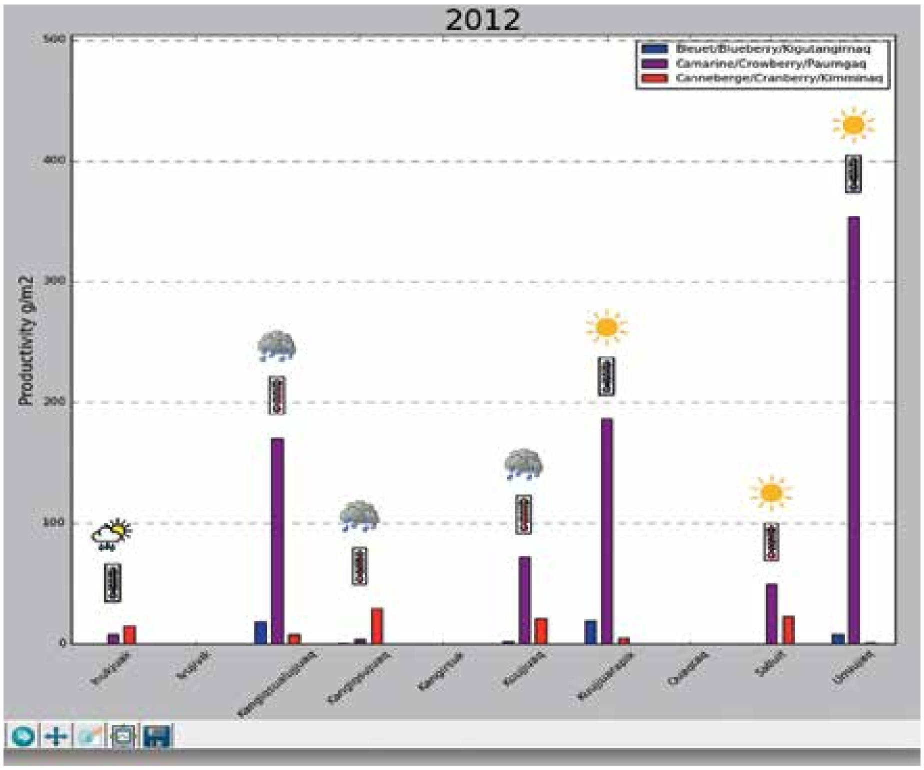

Figure 10. Screen shot from the graphing tool developed to show the berry harvest data from schools in communities participating in the Avativut program in Nunavik. The tool is linked to historic climate data for each community from the Environment Canada data base.

across Nunatsiavut, Nunavik and Nunavut (Gérin-Lajoie et al. 2016; Kugluktukmiut Elders & Youth and Desrosiers 2016). These books were both highly praised for their contribution to local and regional Inuit knowledge, and show the importance of including these approaches in studies of environmental change in the Canadian Arctic. Sheila Watt-Clouthier had high praise for the book The Caribou Taste Different Now: "The Pan-Canadian/cross-community collaborative effort in this important publication, which brings together the Elders and knowledge holders as they share their observations, is absolutely invaluable." The book also enjoyed notice as a recommended book in the CBC Holiday Gift Selection Guide (http://www.cbc.ca/books/holidaygiftguide2016/). It was also the subject of an article in Nunatsiaq News (http://www.nunatsiaqonline.ca/stories/article/65674the_caribou_taste_different_now_say_inuit_inuit_elders/), and in interviews on CBC and RCI (http://www.rcinet.ca/fr/2016/07/26/caribou-gouter-inuits-changements-climatiques-arctique/; http://www.cbc.ca/beta/news/canada/north/book-inuit-elders-on-climate-change-arctic-1.3681168). In addition the HTO in Kugluktuk were delighted with The Berry Book when it arrived in their offices, and we have received many similar messages from Kugluktukmiut.

Natural health products: Rhodiola rosea

The potential for establishing an Inuit owned business in Nunatsiavut based on products from Roseroot continued to be explored. A meeting with the Nunatsiavut finance minister during the Inuit Studies conference in St. John's indicated strong interest in the project, and we were encouraged to submit a business opportunity analysis to the minister. In addition, our research on the growth and phytochemistry of the plant showed there are difference among populations, and

Figure 11. Poster developed for the Avativut Program to increase awareness in the communities and schools of Nunavik.

that the southern populations in Nunatsiavut have the highest concentrations of active ingredients in *Rhodiola*. These studies will help to guide efforts in harvesting wild plants and in choosing populations for cultivation trials.

Syntheses and Database Activities

The analysis of the berry productivity data that have been collected since 2008 in some of the communities and research sites, is a major milestone in our project. This is the first such data base in Canada and it shows there are important variations in production in relation

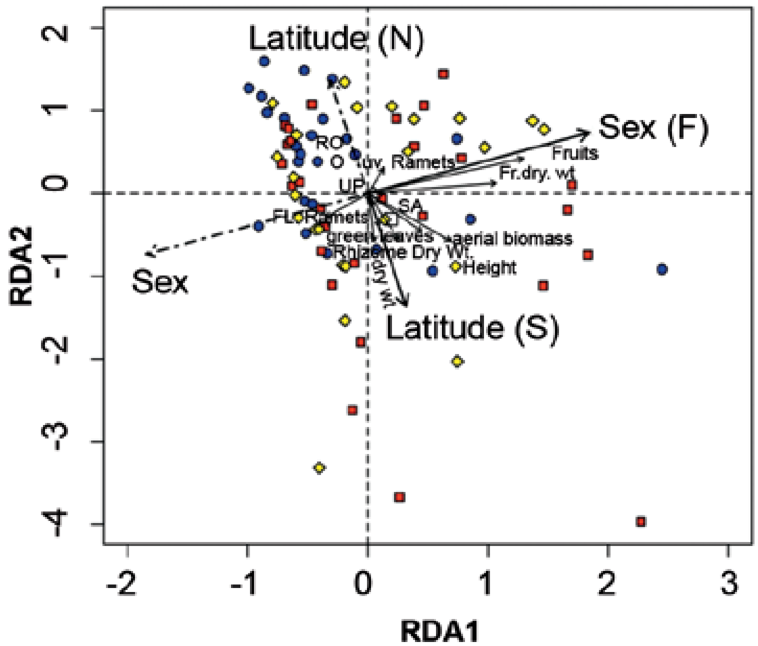

Figure 12. Redundancy Analysis of growth variables (height, fruit weight, numbers of ramets and leaves) in populations of Rhodiola rosea in Nunatsiavut. Substrate types included sandy (SA = red filled symbols), rocky (RO = blue symbols) and Upper beach (UP = yellow symbols). The length of the vectors indicate the strength of the variable in explaining the pattern among populations.

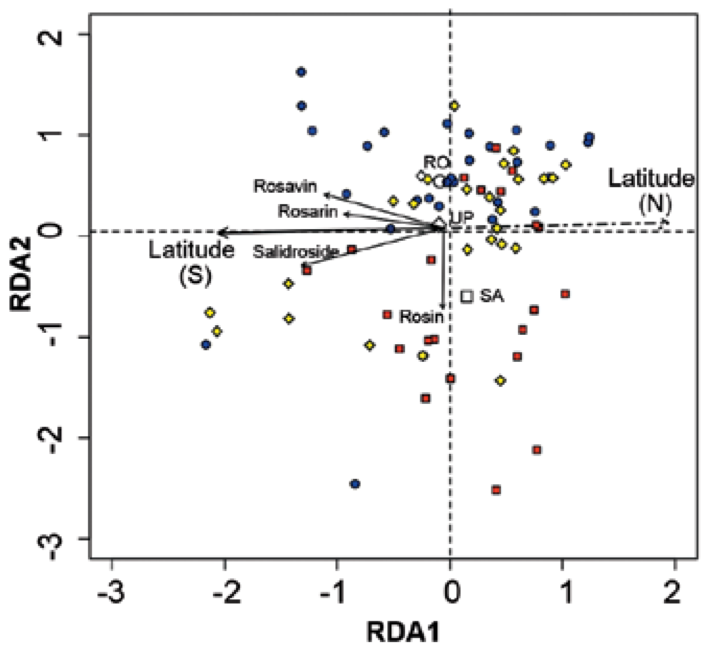

Figure 13. Redundancy Analysis of phytochemistry constituents (Rosavin, Rosarin, Rosin, Salidroside) in populations of Rhodiola rosea in Nunatsiavut. Substrate types included sandy (SA = red filled symbols), rocky (RO = blue symbols) and Upper beach (UP = yellow symbols). The length of the vectors indicate the strength of the variable in explaining the pattern among populations.

to climate, location and the local environment. The data base and analysis will be a complement to the recent analysis of a 40+ year record of berry productivity in northern Finland (Boulanger-Lapointe 2017). This information confirms some of the same patterns that emerged from the observations by community members (Gérin-Lajoie et al. 2016; Kugluktukmiut Elders & Youth and Desrosiers 2016). Continued monitoring of these important species will contribute to understanding responses of Arctic terrestrial systems to the changing climate, and to training of Inuit and other northern youth in scientific monitoring along side traditional and local knowledge.

The regional synthesis of Indigenous observations and climate data by Rapinski et al. (2017), is based on novel analysis methods we developed for a similar synthesis across communities in our project. We continue to work on this synthesis, which will be submitted to and interdisciplinary journal. The ability to analyze Inuit observations and scientific data together has been an objective in our group for many years.

The next steps in our efforts will be to ensure the legacy of the observations and the data collected over the course of the ArcticNet project are properly archived and available for use by communities and other stakeholders. We especially wish to have as much of the monitoring activities continue in the communities as possible, and for participants to continue to contribute information to a regional data base. We have decided to use the easily available platforms offered by Google, that are linked to Google Maps and Google Earth and allow users to develop and link data bases that can be displayed in many different ways. We are set to attend workshops for more information and training on the use of these platforms, and intend to pass this onto interested participants in communities in the next year.

CONCLUSION

- All areas of the Canadian Arctic are showing changes in response to climate change, with vegetation change and increases in permafrost disturbance observed in communities and in scientific studies.
- Berry productivity is greatest in open, relatively dry habitats in Low Arctic sites (bioclimatic zone D) beyond the forest-tundra.
- Observations from elders and studies of berry productivity in relation to shrub cover indicated increased shrub cover in the future will negatively affect berry plants.
- Community-based monitoring of environmental variables is most successful when driven by community needs, as in the water quality monitoring of the George River near Kangiqsualujjuaq by youth as part of a Science Land Camp.
- Teacher training in the Avativut program ensures the program is delivered properly and benefits from Inuit and non-Inuit teachers working together.
- Publication of two books based on interviews with Elders on their observations of environmental change has been widely praised as the type of research needed for communities and for better understanding of the changes in the Arctic.
- The Nunatsiavut government has shown strong interest in the development of a natural products business based on Labrador Roseroot.
- Roseroot populations from southern areas of Labrador showed the highest growth rates and concentrations of active phytochemicals.
- Our data continue to be used in global syntheses of tundra ecosystem responses linked to the International Tundra Experiment (ITEX).
- An important goal in the next year is to ensure the legacy of the observations and data collected over the course of the ArcticNet project are properly archived and available for use by communities and other stakeholders.

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POLAR DATA MANAGEMENT FOR NORTHERN SCIENCE

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ABSTRACT

The Polar Data Catalogue (PDC) at the University of Waterloo is one of Canada's primary on-line sources for data and information on research in the polar regions. Formed as a partnership between ArcticNet, the Canadian Cryospheric Information Network (CCIN), the Department of Fisheries and Oceans Canada, and Noetix Research Inc., the PDC was created nearly 10 years ago as a long-term repository and online access portal to serve the data management needs of ArcticNet scientists and to facilitate the exchange of information among researchers, northern communities, international programs, the public, and other user groups. Since its online launch in 2007, the PDC has grown to include nearly 1800 descriptive records of datasets and polar data resources and 160,000 data files and satellite images from ArcticNet and a wide variety of other Canadian and international research and monitoring programs.

In this project, Polar Data Management for Northern Science, the PDC and CCIN will continue and extend the data management support that we provide to ArcticNet scientists and students who contribute their valuable data to the repository. We will streamline and simplify the data submission process by improving our online tools and will expand visibility of ArcticNet's data by sharing the PDC collections with other polar data portals through global interoperable linkages. We will seek new partnerships with northern partners and research and monitoring programs to coordinate polar data management in Canada and to ensure long-term relevance and sustainability. Along with increasing participation in the global data management community, these activities will secure ArcticNet's long-term data legacy and strengthen the PDC so that the ArcticNet data placed in the PDC now will be available for decades or centuries into the future.

KEY MESSAGES

- Each year, the focus on data sharing and proper stewardship increases in the Canadian and international communities. Data management is rapidly becoming a formal requirement for research granting and coordinating agencies around the world.
- The Polar Data Catalogue (PDC, https://www.polardata.ca) was developed in the mid-2000s as a data management system for ArcticNet scientists. Co-developed by ArcticNet, the Canadian Cryospheric Information Network (CCIN, https://www.ccin.ca/) at the University of Waterloo, and numerous other contributing partners, the PDC places ArcticNet researchers at the forefront of meeting increasing national and international expectations for effective stewardship of publicly-funded research data and information.
- In addition to archiving ArcticNet research, the PDC provides a public access portal for a variety of Canadian and international polar research programs so that their data are freely available on the Internet. Target users of the data are Arctic and Antarctic researchers and students, residents of northern Canada, and policy- and decision-makers with northern mandates.
- The PDC team works continuously to develop and improve the online tools offered on the CCIN website and the PDC and to provide a secure preservation infrastructure for ArcticNet and other partners. Online traffic to our websites has increased during the past year, with views and downloads of metadata, data files, and satellite imagery growing substantially as our collections and outreach activities continue to mature.
- Technical progress in 2016-2017 includes release of a completely new PDC Metadata and Data Input online application, with a simplified and more modern design. It is available in both English and French in order to further meet the needs of our users. Additional achievements

include creation of a new online sea and lake ice data visualization and inclusion of ArcticNet mooring data and more than 160 new GIS datasets into a completely redesigned Map Viewer in the PDC Search online application.

- Digital Object Identifiers (DOIs) have been assigned to 346 PDC datasets, including 56 ArcticNet datasets. Assignment of a DOI is equivalent to publication of a dataset, rendering these data citable and more visible to the research community and increasing scientific discovery as well as opportunities for professional collaboration.
- Progress was made this year in inventorying datasets and working with ArcticNet and other partner programs to complete their metadata contributions to the PDC. Seventy-one new ArcticNet metadata records and 11 new datasets were entered into the PDC, for a total of 943 approved ArcticNet metadata and 106 datasets, comprising 2,442,691 datafiles.
- Two historic full-continent satellite mosaics of Antarctica from 1997 and 2000 were added to the PDC, complementing the 2008 mosaic which was released on the PDC in 2014.
- In 2016, the PDC became a regular member of the International Council for Science World Data System (ICSU-WDS) and was named Canada's National Antarctic Data Centre. These achievements underscore the high standards toward which the PDC strives and symbolize the quality, security, and robustness of the PDC as a data archive.
- Further visibility of the PDC within the research and data management communities was gained though active participation in provincial, national, and international conferences. CCIN staff contributed to international and Canadian data management activities through participation in a variety of Arctic and Antarctic data management committees and organizations.
- Support for purchase of new hardware infrastructure will need to be acquired in 2017 in order for the PDC to continue to provide exemplary data archiving services to ArcticNet and other research groups, allowing provision of Arctic and Antarctic information to the public and our many other users.

OBJECTIVES

This project, Polar Data Management for Northern Science, continues to expand the data stewardship infrastructure first envisioned by ArcticNet and CCIN more than 10 years ago. To ensure ArcticNet's long-term data legacy, we support ArcticNet and its researchers through continuation of effective data archiving and development of the PDC system. The overall objectives of this project, in direct support of data management for ArcticNet, are as follows:

1. Support ArcticNet researchers to create, prepare, submit, and update their projects' metadata records and data files in the PDC, so that the legacy of ArcticNet research is available on the Internet for researchers, northern communities and organizations, international programs, and future generations;
2. Increase partnerships with northern and Inuit organizations and people in Canada, such as Inuit Tapiriit Kanatami (ITK) and the Inuit Research Advisors, to make the PDC more useful to northerners and to meet their data management needs, including project tracking and licensing in northern communities;
3. Improve the online PDC Geospatial Search, PDC Metadata/Data Input, and PDC Lite Search tools to better serve ArcticNet researchers, northerners, and other users;
4. Maintain and improve PDC hardware, software, and security infrastructure, including exploring options for cloud-based preservation and accessibility of the PDC data collections;

5. Help lead the international effort to build an automatic polar metadata interoperability network to facilitate wide dissemination of the PDC collections and to make external research datasets and resources available to PDC users;
6. Use the CCIN website to enhance outreach and education about Canada's north to students and the public; and
7. Secure operational funding for long-term sustainability of the PDC.

Funding from ArcticNet makes it possible to reach these goals as well as improve and strengthen the PDC, so that ArcticNet data placed in the PDC now will be available in perpetuity.

CCIN and PDC also pursue program-wide goals that bring benefit to ArcticNet. Activities to reach these goals are co-funded by PDC partners, with the end result that all participants contribute to, and benefit from, enhancements to the PDC infrastructure and growing data archive. These additional goals are:

8. Provide data management services to relevant polar-related programs in Canada and abroad to steward and make available in the PDC their metadata and data products;
9. Engage with Canada's scientific funding agencies to strengthen and coordinate data stewardship and data management planning and policies in Canada and encourage open access to data, where possible; Increase participation with the international data management community to ensure the PDC system, infrastructure, and data collections are following the latest best practices with respect to new technology and standards;
10. Train and educate researchers and students in data management principles and practical use of the PDC;
11. Formalize an outreach and communication program, including to school children, to heighten awareness of data management principles and ensure visibility and maximal use of PDC and CCIN resources;
12. Quantify CCIN and PDC services and associated costs for data management;
13. Archive, serve, and link to satellite datasets that are of interest to the Canadian cryospheric and remote sensing research communities; and
14. Rescue polar data, particularly from Canadian programs, as time allows and opportunities present themselves.

KNOWLEDGE MOBILIZATION

The following activities were undertaken to disseminate information about the PDC, polar data management, and the polar regions to researchers, students, and other interested stakeholders:

- Eight presentations were given at scientific conferences (please see the Publications section for published abstracts, and Outreach Communication, and Service in the Activities section for more details):
  - One at the Scientific Committee on Antarctic Research (SCAR) Biennial Meetings & Open Science Conference, Kuala Lumpur, Malaysia
  - Three at SciDataCon 2016 in Denver, CO
  - One at the Canadian Association of Geographers of Ontario conference, University of Waterloo
  - Two at the 2016 ArcticNet Annual Scientific Meeting, Winnipeg
  - One at the Arctic Biodiversity Symposium, Ottawa
- Two sessions were co-chaired by CCIN staff at SciDataCon 2016 in Denver, CO:

   - » The Northern Voice: Listening to Indigenous and Northern Perspectives on Management of Data in Canada
   - » Sharing and Accessing Polar Data and Information in Canada and Globally

- Two presentations on the importance of proper data stewardship, evolving expectations regarding sharing data, and accessing and contributing data to the PDC were given to a seminar course at the University of Waterloo.
- A briefing note was published in the 2016 Arctic Yearbook describing how the PDC can be a vehicle for collaboration, northern community partnerships, and policy-making for the Arctic Council and other organizations.
- A one-page infographic was created (Figure 1) with introductory information on the PDC, and was distributed at conferences.
- The PDC Twitter and Facebook accounts were very active this year (please see Outreach, Communication, and Service in the Activities section).
- The 2008 RADARSAT Antarctic mosaic archived in the PDC was published in an online compendium of 20 years of satellite images of the polar regions. We also compared Antarctic mosaics from 1997, 2000, and 2008 and showed ice loss at the margins of the continent (Figure 2).
- A new online data visualization was created to help the public see changes in sea ice and lake ice[1].
- This and other data visualizations on the CCIN website were advertised in an article published in Waterloo Stories[2], the University of Waterloo's online magazine.
- A new webpage about the CCIN/PDC was created on the University of Waterloo website[3] which creates a presence on the University's website and directs interested users to the main CCIN/PDC websites.
- The PDC was entered into a variety of online databases and lists of data access portals, including SSHRC's Digging Into Data list.
- Planning is underway for the second Canadian Polar Data Workshop, following the successful first Canadian Polar Data Workshop in 2015.

INTRODUCTION

When ArcticNet began in 2004, a major challenge was to establish a data management system for the vast amounts of research information soon to be produced by more than 150 researchers and over 1000 graduate students, postdoctoral fellows, research associates, and technicians. To address this challenge, ArcticNet partnered with the Canadian Cryospheric Information Network (CCIN), the Department of Fisheries and Oceans Canada (DFO), and Noetix Research Inc. The result of this partnership was the Polar Data Catalogue (PDC, https://polardata.ca), launched online in 2007. The PDC is housed at the CCIN at the University of Waterloo, where cryospheric data and information management have been ongoing since the mid-1990's. The PDC began as a "metadata database" of records describing the spectrum of ArcticNet research, from the natural, social, and health sciences, to policy, economics, and other disciplines. The mandates of the PDC, and of CCIN, are as follows:

- To provide a data and information management infrastructure for the Canadian polar research community;
- To facilitate exchange of information about the polar regions between researchers, northern communities, international programs, decision makers, and the public; and
- To enhance public awareness and access to polar data and related information.

[1] *https://ccin.ca/home/ccw/seaice/current/thickness*
[2] *https://uwaterloo.ca/stories/check-out-changes-arctic-sea-and-lake-ice*
[3] *https://uwaterloo.ca/canadian-cryospheric-information-network/*

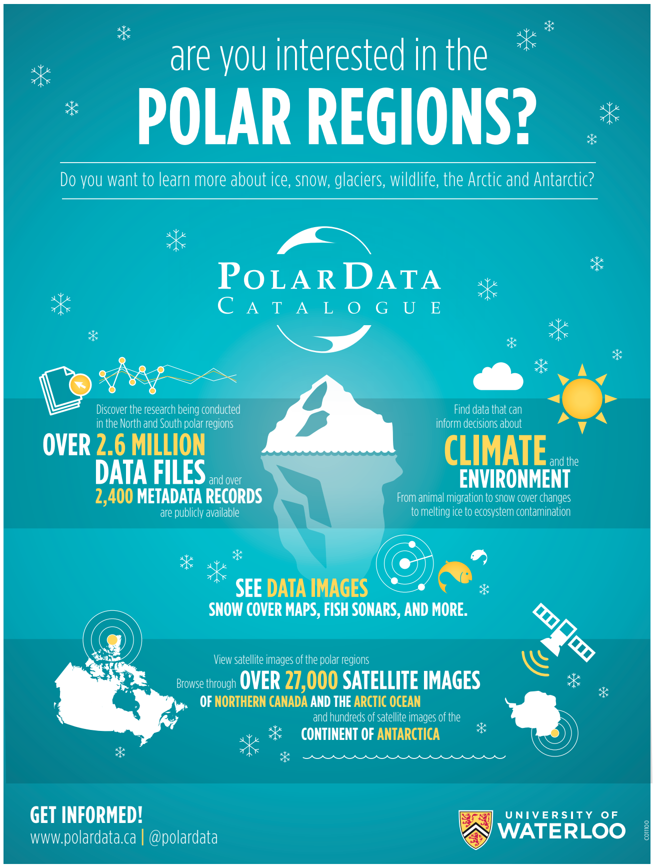

Figure 1. Infographic for the PDC.

Since its launch in 2007, there has been an increasing demand for proper stewardship of valuable Arctic and Antarctic research datasets and information, and a data ingest capacity has been added to the PDC. As a result, a number of other programs besides ArcticNet have chosen the PDC to manage their data. Thanks to the hard work of data stewards at the PDC and ArcticNet, who have worked with researchers and other data experts across Canada and the world, the PDC has developed into a robust, internationally standards-compliant online database.

While ArcticNet continues to foster the growth of the PDC, there has been a cultural shift in the perception of data accessibility. There is a strong movement towards "open access" of data, whereby scientific research information should be made freely available to whomever seeks it. In fact, in 2016, a group of European leaders proclaimed that "…all scientific papers should be freely available by 2020…" (Enserink, 2016). The Canadian Tri-Council has also mandated open access for publications resulting from funded projects[4]. In addition, the International Council for Science has endorsed open access to scientific records (ICSU, 2014), leading the way for many other organizations to do the same. Besides accessibility to information, open access allows for the opportunity for data to be combined and synthesized in non-traditional or unexpected ways, leading to important new insights (Anonymous, 2009; Parsons et al., 2011). With its active participation in the PDC, ArcticNet is thus in a world-leading position for supporting long-term access to and stewardship of Canada's polar research data.

As will be seen in this report, the profile of the PDC continues to grow on both the national and international levels. This underscores the quality of work of the ArcticNet data management team. Recognition of our progress has been demonstrated on numerous occasions, including with the ArcticNet international review panel during their mid-term evaluations. The PDC's increased participation with the global community of scientific data managers enhances our services and expertise, and facilitates wider dissemination of our data and metadata collection. This places ArcticNet and its researchers at the forefront of shaping national policy and of meeting evolving national expectations. This also ensures that Canada contributes to the success and coordination of polar data management around the world and ensures that PDC systems are carefully built and maintained so that the incoming data will be available as widely as possible, now and for future generations.

ACTIVITIES

Specific tasks undertaken this year, which have not been listed in the Knowledge Mobilization section above, are outlined below, with further details provided

[4]*http://science.gc.ca/eic/site/063.nsf/eng/h_F6765465.html?OpenDocument*

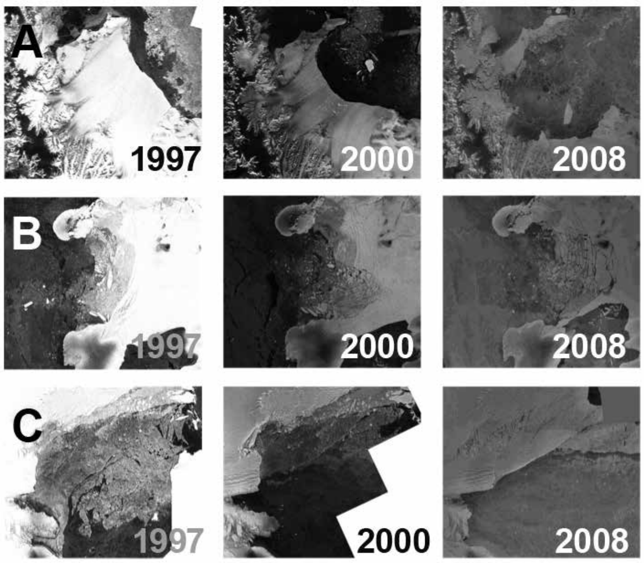

Figure 2. RADARSAT 16-bit detail of the Larsen ice shelf (A), the Wilkins ice shelf (B), and Shackleton ice shelf (C), September-December 1997, 2000, and 2008. RADARSAT imagery COPYRIGHT: © MacDONALD, DETTWILER AND ASSOCIATES LTD. (2008) – All Rights Reserved. RADARSAT is an official mark of the Canadian Space Agency.

subsequently on the more substantial tasks. The tasks below pertain to and directly benefit data management for ArcticNet:

- Supported ArcticNet researchers to create, prepare, and submit to the PDC metadata and data files for their projects, including data from the Amundsen for 2004-2016.
- Improved the PDC Search application according to user input and improving technology, to enhance functionality and streamline future maintenance.
- Enhanced and maintained the CCIN/PDC computer infrastructure by updating server hardware, security, and backup functions.
- Represented Canada and the PDC in national and international data activities and increased collaborations with data-related organizations through service on committees and convening data-related sessions at conferences.
- Worked with colleagues from polar data portals in Canada and in other countries to expand and standardize the automatic polar metadata interoperability network.
- Hired a Project and Outreach Coordinator.

The tasks below have been co-supported from other sources and/or indirectly benefit ArcticNet through improved coordination and implementation of polar data management in Canada:

- Sought arrangements for long-term support to sustain the PDC and pursued opportunities for significant new development funding.
- Designed a new PostgreSQL database, an open-source alternative to Oracle, which will facilitate offsite replication of the PDC database and system and permit operational flexibility as we grow.
- Drafted Data Deposit/Access Agreements for use with POLAR researchers and others working in and around Cambridge Bay which can also be used by other partner programs.
- Continued to work with staff from the Global Change Master Directory (GCMD) in the US to arrange for conversion of PDC metadata to the GCMD format, an activity required by our new status as Canada's National Antarctic Data Centre.
- Uploaded approximately 20 TB of PDC data files to a new preservation system at Scholars Portal, Ontario Council of University Libraries (SP/OCUL), headquartered at the University of Toronto.
- Updated the scientific and graphical content of the CCIN website, using input from the Scientific Advisory Council.
- Moved the entire CCIN website to a new server to improve security.
- Updated the PDC online Help Manual with information on the new PDC Metadata and Data Input and PDC Search applications.

- Explored and installed data sharing tools on our infrastructure in collaboration with the Marine Environmental Observation Prediction and Response (MEOPAR) Community of Practice.
- Audited old metadata which required updating or had outstanding issues.
- Improved our internal organization through formal task tracking.

ArcticNet Metadata and Data Management and Stewardship

This year, 71 new ArcticNet metadata records and 11 new datasets have been added to the PDC, for a total of 943 total approved metadata and 106 total datasets, comprising 2,442,691 datafiles. Further details are in the ArcticNet Project Metadata List (to be sent separately to ArcticNet management) and in the Results section of this report. The ArcticNet Administrative and Data Coordinator at U. Laval, C. Gombault, allocated considerable time to organizing and uploading to the PDC the diverse ship datasets collected on the CCGS *Amundsen* since 2003, particularly CTD (Conductivity-Temperature-Depth) casts, mooring data, Navigation (NAV) data and Moving Vessel Profiling (MVP) data, to ensure their security and facilitate long-term archiving.

The PDC Data Manager at CCIN in Waterloo, G. Alix, is responsible for reviewing and approving all ArcticNet metadata and data submissions. She makes numerous contacts with researchers, especially with respect to data preparation, submission, and review. She has reviewed contributed ArcticNet metadata and data files and has approved them for public release, as appropriate.

PDC Online Application Development

At the time of our 2015-2016 Report, the PDC Metadata and Data Input application had been completely rebuilt using the latest technologies and tools. It was anticipated to go online in mid-2016. Not only did we reach that goal, but the application has also been translated into French. Users now have the option to use either official language to enter or update metadata and data in the PDC.

Next to be rebuilt is the PDC Search application which is currently in progress. Similar to the PDC Metadata/Data Input application, the new PDC Search application will incorporate the latest web technologies as well as a more modern look and simplified design.

Hardware, Infrastructure, and Security

The CCIN/PDC computer server and storage infrastructure, purchased in 2011 and installed in 2012, is reaching its end of life. We have received quotes from computer hardware vendors which indicates the cost of replacing our on-site production system will be substantial, and we have been searching for funding. We have also been anticipating for a number of years the need to replicate the PDC in other locations such as Cambridge Bay in the future, so we are transitioning away from Oracle to PostgreSQL, an open-source alternative to Oracle which is used by a majority of polar data centres around the world.

New Partnerships and Support

In November 2016, the CCIN/PDC was officially made a member of the World Data System of the International Council for Science[5]. Indeed, we are the 100th member and the WDS wishes to make a bit of publicity about this. The other Canadian members are Ocean Networks Canada and the Canadian Astronomy Data Centre/Canadian Virtual Observatory. This is a significant honour and also entrance into an international group of data centres with high standards of ethics, procedure and protocols that will be a major asset to the CCIN/PDC in the future.

Secondly, we have completed the integration of the CCIN/PDC into the University of Waterloo's

[5]*http://icsu-wds.org/community/membership/regular-members?fid=canadian-crysopheric-information-network-polar-data-catalogue*

Interdisciplinary Centre on Climate Change[6] (IC3) under the Directorship of Dr. Daniel Scott. This transition will not affect the day-to-day operations of CCIN/PDC, yet will provide an ongoing home within the University of Waterloo's institutional governance and also link us to other climate-related initiatives and granting opportunities on campus. Dr. Julie Friddell will become the Director of CCIN/PDC in the near future.

Successful proposals or letters of intent to support and expand PDC and CCIN activities were prepared this year for existing and new partners at NCP, POLAR, NGMP, ArcticNet, and ECCC. Support for co-op students was also provided by the Faculty of Environment of the University of Waterloo and the Marine Environmental Observation Prediction and Response Network (MEOPAR). Unsuccessful proposals and Letters of Intent, most with partner organizations, were sent to the Canadian Foundation for Innovation's (CFI) new cyberinfrastructure initiative, the Social Sciences and Humanities Research Council of Canada (SSHRC), the Networks of Centres of Excellence's International Knowledge Translation Platforms competition (proposal entitled Sharing Arctic Knowledge across Cultural, Disciplinary, National and Technical Boundaries: The Arctic Data Network), and Horizon 2020 of the European Union. There were three SSHRC proposals: one for the Arctic Marine Use and Transportation Project (AMUT), a Canadian consortium led by Jackie Dawson of the University of Ottawa; a second for a multi-institutional partnership for Arctic data management led by CCADI; and a third, which was a Knowledge Synthesis grant, that would synthesize information about how data centres are currently used by circumpolar communities and how these data centres could be made more useful. Horizon 2020 proposals were coordinated via our partner Polar View and included Arctic-UNION and Enhanced Leveraging of e-Infrastructures for Polar Scientific Exploitation (ELIPSE), both of which focused on Arctic data exchange and accessibility through metadata and data interoperability. Finally, an unsuccessful Notice of Intent was submitted for the Natural Sciences and Engineering Research Council of Canada (NSERC) Research Tools and Instruments (RTI) program, intended to fund the replacement of CCIN/PDC's ageing hardware infrastructure.

These activities, whether successful or unsuccessful, have strengthened relations with many new and existing partners. Although we will continue to seek funding for these activities, the results outlined above illustrate the difficulty in securing funding for these types of projects at both the national and international levels. This difficulty in securing funding for data management and data stewardship activities is shared by our partners from dozens of institutions around the world. The fact that we have been so prolific in submitting so many applications shows the degree of interest in our work in the polar data management community, motivation and enthusiasm that will hopefully continue in the coming years.

Outreach, Communication, and Service

On Twitter we have 334 followers, up from 193 last year, and we have made over 2,600 tweets. Our Twitter and Facebook accounts are linked such that any tweets posted on Twitter are automatically posted on Facebook. The reach of our social media efforts is increasing as evidenced by the increase in retweets and "likes," including by well-known organizations such as Maclean's magazine, of new metadata and data, news stories, and posts from conferences attended by CCIN staff.

Presentations were made locally at the University of Waterloo as well as at international and Canadian conferences as follows. Please see the Publications section of this report for a list of those presentations whose abstracts were published this year.

- Alix, G., Oral presentation, Data Management for Geographic Science, GEOG 600 – Seminar in Spatial Data Handling, University of Waterloo, Waterloo, ON (March 2016).

[6]*https://uwaterloo.ca/climate-centre/*

- Alix, G., Antarctic Data and Information for Canada: The Polar Data Catalogue. Poster presentation, Scientific Committee on Antarctic Research (SCAR) Biennial Meetings & Open Science Conference, Kuala Lumpur, Malaysia (August 2016).
- Church, D., The Northern Voice: Listening to Indigenous and Northern Perspectives on Management of Data in Canada. Oral presentation, SciDataCon 2016, Denver, CO, USA (September 2016).
- Church, D., Sharing and Accessing Polar Data and Information in Canada and Globally. Oral presentation, SciDataCon 2016, Denver, CO, USA (September 2016).
- Church, D., The Canadian Cryospheric Information Network and Polar Data Catalogue. Poster presentation, World Data System (WDS) Members' Forum, Denver, CO, USA (September 2016).
- Alix, G., Listening to the Users: Improving Online Tools and Data Access at the Polar Data Catalogue. Oral presentation, 2016 Canadian Association of Geographers of Ontario (CAGONT) Conference, University of Waterloo, Waterloo, ON (October 2016).
- Alix, G., The Polar Data Catalogue: Data and Information for Canada and the World. Oral presentation, 2016 ArcticNet Annual Scientific Meeting, Winnipeg, MB (December 2016).
- Alix, G., Keeping your Data Safe: How to Organize and Protect your Data. Oral presentation, 2016 ArcticNet Student Association Student Day, ArcticNet Annual Scientific Meeting, Winnipeg, MB (December 2016).
- Alix, G., Oral presentation, Data Management for Geographic Science, GEOG 600 – Seminar in Spatial Data Handling, University of Waterloo, Waterloo, ON (January 2017).
- Friddell, J. E., Data Management for Biodiversity, Oral presentation, Canada's Arctic Biodiversity Symposium, Ottawa, ON (January 2017).

In addition, in May 2016, J. Friddell and representatives of IC3 (D. Scott, S. Brown, S. Elliott) met with Miguel Rodrigues, the Arctic contact at the US Embassy in Ottawa, to introduce the PDC and discuss data issues with respect to research in the two countries. Also in May 2016, an oral report on the 2015 Canadian Polar Data Workshop and the 2015 Polar Data Forum II were given to NSERC and the Tri-Agency policy group. The outcomes and recommendations from the meetings seemed very well received. We are looking for ways to follow up from the meetings regarding the future of data management in Canada, including implementing data management plans, advance and support data policy, as well as securing funding for CCIN/PDC.

Further, J. Friddell, CCIN Director, served in the following capacities:

- Canadian representative, Arctic Data Committee of the International Arctic Science Committee and Sustaining Arctic Observing Network, leading a project on standardizing the minimum information required for effective metadata sharing
- Member, Canadian Tri-Agency Data Management Policy Advisory Committee
- Member, Scientific Advisory Committee, Environment Climate Data Sweden
- Member, Canadian Committee on Antarctic Research
- Member, with G. Alix, of the Standing Committee on Antarctic Data Management of the Scientific Committee on Antarctic Research
- Representative to the Group on Earth Observations Cold Regions Initiative (GEOCRI)

Canadian and International Polar Data Management Activities and Strategic Planning

The PDC as Canada's National Antarctic Data Centre

Article III of the Antarctic Treaty states, "Scientific observations and results from Antarctica shall be exchanged and made freely available."[7] In Canada this is finally possible, now that the PDC was named Canada's National Antarctic Data Centre. This gives the PDC a new opportunity to serve the Canadian polar research community. It also gives us, and ArcticNet as well as ArcticNet data, more international visibility in the Antarctic community. In addition, being named Canada's Antarctic Data Centre brings awareness to good data management practice to those Antarctic researchers who may have not been exposed to good data stewardship practices to date.

The Second Canadian Polar Data Workshop

Planning is underway for the second Canadian Polar Data Workshop (CPDW) to be held in Ottawa May 30-31, 2017. This is a follow-up to the highly successful first CPDW that occurred in May 2015. The objectives of the second workshop are to coordinate polar data management activities in Canada as well as work on specific action items that were raised during the 2015 workshop. The meeting will be structured to reach specific outcomes through working sessions and consensus building on themes of policy, funding, collaboration, and governance structure.

We intend for the discussion to be as inclusive as possible, and thus we are inviting all rights holders and stakeholders interested in data management issues for the Arctic and Antarctic regions to participate. We are currently working to secure travel funding for northern participants.

The Planning Committee of the second CPDW has been holding monthly teleconferences and consists of the following members:

- G. Alix (CCIN/PDC)
- D. Church (CCIN/PDC)
- J. Friddell (CCIN/PDC)
- C. Herbert (Coordinator, Lake Winnipeg Basin Information Network)
- S. Nickels (Director, Inuit Qaujisarvingat and Senior Science Advisor, Inuit Tapiriit Kanatami)
- P. Pulsifer (Research Scientist, University of Colorado, Boulder)
- J. Sokol (Senior Analyst, Polar Knowledge Canada)
- S. Tomlinson (Environmental Scientist, Northern Science and Contaminants Research Directorate)

The Planning Committee is in the process of inviting participants for an Advisory Committee which will assist in steering the planning process and ensure that the second CPDW meets the community's needs.

Draft Strategic Plan for CCIN/PDC

A draft strategic plan for CCIN/PDC was circulated at the Polar Data Management Committee (PDMC) meeting on December 8, 2016. This document is meant to provide guidance at a high level, outlining the mission, identity, and objectives of the CCIN/PDC, and providing an action plan for the next five years. The PDMC was asked to provide written feedback this winter with a teleconference scheduled for March 2017.

RESULTS

In January 2017, traffic on the PDC sites (www.polardata.ca: PDC Search application, PDC Lite, and PDC Metadata/Data Input) and the CCIN website (www.ccin.ca) included 4,450 visits, 3,256 unique visitors, and 9,655 page views. On an annual basis, the PDC and CCIN websites saw visits which resulted in 33,861 sessions during 2016, an increase of nearly 10% over 2015. Since 1 January 2016, there have been 2,493 downloads of PDC data files, 5,645 downloads of Arctic RADARSAT images, and 236 downloads of Antarctic RADARSAT images. Most visitors to the PDC and CCIN websites were from Canada but there have also been visitors from the US, Norway, the UK, Germany, Iceland, Russia, Australia, and other countries.

[7] *http://www.ats.aq/e/ats.htm*

Metadata and Data in the PDC

As of 1 February 2017, the number of PDC metadata records from all programs reached 2,654 with 22 in the SUBMITTED state, 5 in the SENTBACK state, 124 in the SAVED state, and 2,503 APPROVED and available publicly. This year, ArcticNet scientists and students have contributed 71 new metadata records, for a total of 943 approved ArcticNet metadata records.

Below is the inventory of metadata from our other partner programs (many metadata are associated with more than one program, so the numbers below add to more than the total number of metadata):

- CEN: 106
- CBMP: 524
- IPY: 732
- CASES (Canadian Arctic Shelf Exchange Study): 86
- ADAPT (Arctic Development and Adaptation to Permafrost in Transition): 206
- NCP (INAC): 152
- BREA (INAC): 136
- APAN (Adaptation Program for Aboriginals and Northerners, INAC): 121
- NGMP (INAC): 36
- POLAR (Polar Knowledge Canada/CHARS): 60
- Reference (for other polar-related data and information portals and websites from around the world): 71

To date, 319 datasets have been submitted to the PDC archive, 109 of which are affiliated with ArcticNet. Eleven of these ArcticNet datasets have been added this year, comprising 5,228 new data files. Of the archived datasets, 285 are available online, with the remainder either not available publicly due to privacy issues, temporary embargoes, or ongoing efforts required to properly organize and archive the files. There is a total of 2,741,066 data files in the PDC, approximately 32 Terabytes in total, consisting of 19 TB of files from research datasets, 8.5 TB of RADARSAT imagery, and 5 TB of data files in our server which include a back up of 1.5 TB for the *Amundsen* Science data, 2.5 TB of satellite images and 1 TB of datasets to be rescued. The satellite images and dataset to be rescued are waiting to be processed, reviewed, and approved before they are available on the PDC.

Outreach and Publications

In partnership with Environment and Climate Change Canada, we administered an online survey in January 2017 entitled "What are your needs for snow and ice data?" to recipients of an ECCC mailing list and to the mailing list used for the 2015 CPDW. In total, over 300 individuals were invited to complete the survey which aims to determine how ECCC and CCIN can improve provision of snow and ice data to researchers, government, organizations, and the public. Analysis of the survey responses is currently underway. Results will be used to inform changes to the CCIN website and the information provided to ECCC.

April 2016 saw the public release of a compendium of 20 years' worth of satellite radar images of the polar regions. This compendium was the work of the Polar Space Task Group of the World Meteorological Organization, and its subsidiary, the Synthetic Aperture Radar Coordination Working Group. The PDC contributed by hosting the 2008 full-continent RADARSAT-2 mosaic of Antarctica, featured on page 13 of the Compendium[8]. The satellite images that have accumulated over the past 20 years have shown acceleration of change over time of snow and ice at the Earth's poles.

Please see the Publications section of this report for a full list of publications that were published this year.

[8]*http://www.wmo.int/pages/prog/sat/documents/SAT-GEN_PSTG-SAR-CWG-DataCompendium-Apr2016.pdf*

DISCUSSION

The PDC continues to evolve into a reliable and recognized repository and access website for ArcticNet metadata and data as well as data and information from Canada's and other countries' Arctic and Antarctic research programs. This year saw major accomplishments in terms of the PDC's visibility, both nationally and internationally: the PDC was named Canada's National Antarctic Data Centre; the PDC became a member of the ICSU-WDS; publication was achieved in the 2016 Arctic Yearbook; and RADARSAT imagery hosted by the PDC was featured in a publicly accessible compendium of 20 years of satellite imagery of the polar regions. These achievements underscore the PDC's reputation as a secure, reliable, trustworthy, and professional data repository. Other achievements highlight CCIN/PDC efforts to remain relevant and up-to-date with technology: the public launch of the new, modernized PDC Metadata and Data Input application, now available in both English and French; the addition of data visualizations on the CCIN website; and the assignment of DOIs to datasets, which allow researchers' data to be citable and more visible.

This year did not see the dramatic ingestion of ArcticNet metadata and data files compared to figures reported for previous years. This can be attributed to a number of factors: the size of datasets varies between projects, and several significant datasets were ingested in previous years; the number of metadata varies between projects; processing time varies for different datasets; and the "availability" of older data to be archived. We want to distribute the Call for Data for ArcticNet data so that we can ensure their entry by the end of ArcticNet in 2018. The legacy of this data depends on researchers' cooperation and participation.

Discussions continue with a growing number of organizations regarding collaborating on polar data management efforts and serving new groups' data stewardship needs. This will culminate with the second Canadian Polar Data Workshop, planned for May 2017. We also continue to seek financial support for replacing our server hardware system, which is nearing its end of life. Such support is critical for sustaining the PDC: a nationally and internationally recognized data repository that is just hitting its stride.

CONCLUSION

Data management is becoming an increasingly formal requirement for research granting, coordination, and publishing agencies around the world. The Polar Data Catalogue, co-developed by ArcticNet, CCIN, and many other contributing partners, prepares ArcticNet researchers and places them at the forefront of successfully meeting the evolving data management requirements and expectations of the Canadian research community. Continued development of the PDC, via support from ArcticNet and other partners, is strengthening effective management of Arctic and Antarctic data in Canada and providing the ability to build and maintain a capable and respected archive for long-term access to the stewardship of Canada's polar research data.

As evidenced by the new partnerships and memberships of the last few years, the progress of the PDC is being recognized at both national and international levels. We are committed to open and public access of metadata and data, interoperability, meeting international standards, and the provision of data security in perpetuity. This gives us the confidence and leverage to work with sponsors toward a sustainable future for the PDC and its data collections.

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KNOWLEDGE CO-PRODUCTION FOR THE IDENTIFICATION AND SELECTION OF ECOLOGICAL, SOCIAL, AND ECONOMIC INDICATORS FOR THE BEAUFORT SEA

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HQP

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ABSTRACT

This network aims to bridge multiple stakeholders, management agencies, and knowledge holders to effectively link ecological changes to the greater health of the ecosystem at the local, regional and circumpolar scales. Arctic ecosystems not only support human well-being and contribute to economies, but they are also under increasing pressure from climate change and resource use. The Inuvialuit Settlement Region (ISR) is home to six communities that rely on resources within the Beaufort Sea for activities such as hunting, trapping, fishing, and whaling. This research program aims to use a multiple evidence based (MEB) approach to bridge diverse knowledge systems, for the development of a comprehensive set of indicators to monitor the marine ecosystem. The overall goal of integrating information across knowledge systems and disciplines will first occur at the local level to develop a better understanding of beluga health and habitat use. This will then be used to develop indicators so assist co-management boards with decision-making. In the second phase, the MEB approach will be used at a regional scale to integrate indicators across social, ecological, and economic disciplines to select a suite of indicators to be used to inform decision-making at the local, regional, and circumpolar levels. In order to manage natural resources effectively, management entities (Oceans Canada, Fisheries Joint Management Committee) are working to select indicators to be used as proxies for identifying change in the region. These include ecological indicators to identify changes in the ecosystem and environment, social indicators to identify changes occurring within the local communities, and economic indicators to identify changes regarding economic activity. The results from this program will enhance marine mammal and ecosystem monitoring in the Arctic by providing insight into processes that foster the coproduction of knowledge towards an improved understanding of the marine ecosystem. In addition, key indicators identified through this program will feed into regional, national and international monitoring programs.

KEY MESSAGES

- This project is using a platform of knowledge co-production among Inuit, government and researchers to identify ecological, social and economic indicators for the Beaufort Sea.
- Inuvialuit and researchers hold different knowledge about beluga, both which can contribute to management decision-making.
- Inuvialuit beluga hunters have consistently reported that beluga look healthy, with the exception of whales in 2014 that appeared to be thinner than usual, although unusual growths or abnormalities were rare and the muktuk and meat were in good or excellent condition.
- Beluga biotracers (stable isotopes and fatty acids) analyses from 2011 to 2014 support an increase in diet diversity in 2014, the same year the unusual occurrence of beluga at Ulukhaktok took place.
- Beluga habitat hot spots in the Mackenzie estuary are dynamic, shifting over space and time in relation to environmental and oceanographic drivers.
- Beluga habitat use of the Beaufort Sea Shelf and offshore are associated with sea surface temperatures and chlorophyll categories suggesting links with prey assemblages (i.e. Arctic cod).
- Traditional ecological knowledge of coastal fish highlighted observed changes in fish health and condition as well as environmental changes in the area (e.g. weather, oceanography and coastal processes).
- Database on regional indicators reveal over 600 time-series datasets for marine monitoring activities.
- Many indicators for monitoring changes in the Beaufort Sea and TNMPA are lacking long-term datasets and require more in depth scientific and traditional knowledge verification so they are useful in capturing changes in the ecosystem.

OBJECTIVES

Objectives are identified in our proposal listed below; that support our overarching objective/goal: to use the platform of knowledge co-production among Inuit, decision makers and researchers to identify ecological, social, and economic indicators for the Beaufort Sea to support long-term monitoring and decision-making:

1. Develop and implement a framework for the co-production of knowledge for the identification and interpretation of indicators at the local scale.
2. Scale from local to regional indicator development for the Beaufort Sea ecosystem.
3. Develop, test and validate a set of regional ecosystem indicators based on different user objectives.
4. Evaluation of knowledge co-production into indicator selection at the local and regional scale.
5. Integrate indicators into a decision-making tool to strengthen linkages between research and policy.

KNOWLEDGE MOBILIZATION

- 10 oral presentations were made at scientific conferences (Canadian Association of Geographers Ontario Conference – Waterloo ON, Oct. 2016; ArcticNet Annual Scientific Meeting – Winnipeg MB, Dec. 2016).
- Seven poster presentations were made at scientific conferences (IMBER ClimEco5 Conference - Natal Brazil, Aug. 2016, ArcticNet Annual Scientific Meeting – Winnipeg MB, Dec. 2016).
- Two project students and one project lead contributed to education outreach (Arctic Climate Change Youth Forum at Winnipeg, MB and presentations at schools in Paultauk, NT and Coolum, Australia; Research as Reconciliation for the Association of Canadian Universities for Northern Studies).
- Four project students contributed to the ArcticNet Students Association (J. Brewster, K. MacMillan, E. Lede, D. Fawcett).
- 79 interviews were held in northern communities (30 in Paulatuk, 17 in Tuktoyaktuk, 32 in Ulukhaktok).
- 76 marine observations were recorded by hunters from Paulatuk and Tuktoyaktuk, and uploaded by two community research assistants (V. Pokiak and D. Ruben) using the mobile Application Survey123.
- This project mentored five Northern research partners (V. Pokiak, A. Gordon, J. Pascal, L. Kikoak, and P. Ahkiatak).
- Eight meetings with co-management boards, management groups and decision makers (Fisheries Joint Management Committee – Jan. 2017; Inuvialuit Game Council – June & Sept. 2016, Mar. 2017; Beaufort Sea Partnership – Oct. 2016; Inupiat-Inuvilauit Beluga Whale Commission Meeting - Aug. 2016, Alaskan Beluga Health Meeting - Nov. 2016; Stock Assessment of Eastern Beaufort Sea Beluga Meeting – Jan 2017).
- Visited six Northern Communities for results sharing workshops and community meetings (Sachs Harbor, Inuvik, Aklavik, Tuktoyaktuk, Paulatuk, Uluhaktok).

INTRODUCTION

Climate change impacts will have implications for ecosystems and the human communities that depend on them (Larsen et al., 2014), and models project that these changes will continue, and in some instances, accelerate in the future (Collins et al., 2013). The cumulative impacts of climate change and multiple anthropogenic stressors (e.g. resource exploration and exploitation) have put arctic marine ecosystems under increasing pressure (SWIPA 2011). The rapid nature of these changes heightens the urgency to identify ways to sustainably manage and govern these ecosystems under changing conditions. To initiate adaptation actions, decision makers need to understand the nature of these changes together with the capacity of the ecosystem and Inuit communities that rely on them to adapt (Smit and Wandel 2006). This involves drawing on all possible sources of information, including local, traditional and western scientific knowledge, to develop a comprehensive understanding of climate-induced changes and the associated ecological and human responses (Pearce et al., 2009; Pearce et al., 2011; Pearce et al., 2012; Pearce et al., 2015). Thus, an inclusive holistic approach, that includes biophysical and human components, is needed to characterize changes in arctic marine ecosystems in a manner that is relevant to Inuit communities and decision-making (Tengo et al., 2014). Inuit, scientists, and resource managers all have vested interests in the conservation and sustainable use of the arctic marine ecosystem (Robinson and Wallington 2012). The inclusion of all knowledge holders and users in developing research and management plans creates an enriched understanding of the changes occurring in arctic marine ecosystems and supports knowledge generation and sharing (Tengo et al., 2014).

Indicators are being used across the Arctic at various scales, including local, regional and circumpolar, to monitor changes in the environment (National Oceanic and Atmospheric Association Arctic report card), biodiversity (e.g. Circumpolar Biodiversity Monitoring Program), and communities (Arctic Social Indicators, Arctic Human Development Report). Indicators can be used to characterize ecosystems in simpler terms, and provide a baseline from which to monitor change and inform management (Jackson et al., 2000). Scientific and local observations of environmental change can be brought together to identify new avenues for further exploration, compare observations from different scales and discuss potential mechanisms that explain both sets of observations (Huntington et al., 2004).

Co-management of wildlife and other renewable resources was established under the Inuvialuit Final Agreement (INAC 1984), and continues at present with Inuvialuit and Department of Fisheries and Oceans (DFO) co-managing marine resources. This process involves negotiation, deliberation, knowledge generation and joint-learning (Berkes 2009), and offers the opportunity to bring together complementary knowledge systems for sustainable ecosystem management (Tengo et al., 2014). The co-production of knowledge is an approach for connecting knowledge systems that engages mutual processes at all stages of knowledge generation, including the setting of goals, the generation of knowledge and the re-assessment of knowledge gaps and new questions (Tengo et al., 2014). Regional management bodies aim to include both Inuit and western scientific knowledge for ecosystem management in the Inuvialuit Settlement Region (ISR) (e.g. Beluga management plan), but few have carried this out using principles of co-production. A “co-production” research framework would assist in the inclusion of diverse knowledge and perspectives in the development of user-specific monitoring objectives, and identification of appropriate indicators and ecosystem linkages to support adaptive co-management (Berkes 2009). Despite our current understanding of recent changes in arctic marine ecosystems, developing and monitoring ecosystem indicators that draw on both Inuit TEK and western science remains in its infancy.

ACTIVITIES

We had an extremely productive second research year during which we completed many community meetings and workshops, prepared results for publication, and analyzed new data that will facilitate the co-production of knowledge for the development of indicators for monitoring change in the Beaufort Sea.

1. Local Scale Beluga Indicators: Includes research projects LEK/TEK Indicator Development and Traditional Ecological Knowledge of Beluga and Change

Community Consultation Meetings: Researchers met with Fisheries Joint Management Committee (FJMC) (Jan 2017), Hunter and Trappers Committees (HTCs) in Paulatuk, Ulukhaktok and Tuktoyaktuk to present and receive feedback on research design, update on research progress, and plan future research activities. Community presentations are expected for March 2017 to return results for this project.

Data collection

a) LEK/TEK Indicator Development: Data collection occurred in Tuktoyaktuk, East Whitefish camp and Paulatuk. In Paulatuk and Tuktoyaktuk, 76 marine observations were completed by community members and uploaded by two community research assistants (V. Pokiak and D. Ruben) using the mobile Application Survey123. Daily observations were collected by a research assistant and TEK holder on Hendrickson Island (L. Kikoak and J. Noksana Sr.) for the duration of fieldwork. Beluga health was characterized at East Whitefish by a summer student from the Aurora Research Institute (Andrew Gordon Jr.) using local indicators based on TEK/LEK observations. In-depth interviews about climate change and vulnerability, including the effects on beluga whale harvests were conducted with Inuit by D. Waugh over a 6-week period in Tuktoyaktuk.

b) TEK of Beluga and Change: Data were collected in the communities of Tuktoyaktuk (June-August 2016), Paulatuk (Dec- Feb 2016), and Ulukhaktok (June-Aug 2016) using through semi-structured interviews (n=17, 30, 32 respectively), along with participant observation (including time at the beluga hunting camp on Hendricks Island, hunting trips, participation in community life and events), and review of secondary sources.

Data analysis and synthesis

a) LEK/TEK Indicator Development: Data verification and analysis is ongoing for TEK interviews conducted in Tuktoyaktuk. Local indicators for beluga health were identified and piloted in 2016. Beluga Observation Application was reviewed in 2016 and a new mobile application was developed using Survey123 based on input from community Focus Group participants and HTCs. This App allowed collection of marine observations in summer 2017 and analysis of these observations is ongoing.

b) TEK of Beluga and Change: Data on TEK of beluga were compiled and analyzed using thematic analysis into five categories: TEK of beluga behaviour/ecology, hunting techniques, subsistence food techniques, values, and observations of change. In Ulukhaktok, the data collected were analyzed together with data collected in 2005. Analysis will focus on longitudinal data sets, as well as the key themes and some individual responses between the 2005 and 2016 studies to understand processes and change.

Communication: the research was communicated by university and local researchers at several local, regional and international opportunities including: school presentations and radio updates in Paulatuk, Ulukhaktok and Tuktoyaktuk; research conferences (e.g. ArcticNet ASM, CAGONT); regional meetings (e.g. Inuvialuit Regional Corporation (IRC) climate change adaptation planning workshop in Inuvik); and manuscripts submitted to Global Environmental Change, Arctic, and Polar Record.

2. Western Science Indicator Development Includes research projects on Beluga Health, Beluga Habitat and Habitat Use, and Fish Niche Assessment

Community Consultation meetings: Researchers communicated with HTCs (Inuvik, Tuktoyaktuk: Beluga Health, Aklavik, Fish Niche Assessment) prior to the field season to discuss ongoing research activities. All components have been presented to Inuvialuit Game Council (IGC) (June and Sept 2016) and FJMC (Jan 2017). Beluga Health and components have provided HTCs with field reports and planning meetings for 2017, with meetings with Inuvik and Tuktoyaktuk HTC in Feb 2017 to discuss the upcoming 2017 field season. Lastly a Beluga Stock Status meeting was held in Inuvik in Jan 2017 where all projects contributed to the assessment on beluga health.

Data Collection

a) Beluga Health: Beluga health sample analysis partnered with harvest monitoring program at three core locations: Hendrickson Island (Tuktoyaktuk harvest site), East Whitefish (Inuvik Harvest site), Darnley Bay (Paulatuk Harvest site). Enhanced health metrics and necropsies were taken at Hendrickson Island where a veterinarian team was based, additional health samples were taken at the nearby location of East Whitefish. These data are being combined with historical datasets to identify long-term trends of beluga health and feed into regional indicator assessments.

b) Beluga Habitat and Habitat Use: Ongoing analysis of aerial surveys in conjunction with the deployment of five moorings equipped with CTDs (salinity and temperature), ADCP (currents), pressure sensors (waves and water depths/tides), hydrophones (whale vocalization and anthropogenic noise) and pH and turbidity sensors. Data collection will also include a land-based weather station equipped with a wind anemometer, air temperature and a series of time-lapse photos and videos to capture beluga observations close to shore.

c) Fish Niche Assessment-Shingle Point Case Study: completion of Shingle Point diet biotracer (stable isotopes and fatty acids) analysis among 16 species (Brewster et al., 2016) and application to defining mercury processes and the use of mercury as a biotracer (Brewster et al., thesis and submitted). Data from this research supports the regional indicator assessment of identifying indicator fish in the Beaufort Sea Shelf food web and comparison with the Ecosim with Ecopath model.

Data analysis and synthesis

a) Beluga Health Beluga health summary and state of knowledge overview research document prepared for the Fisheries and Oceans Canada Eastern Beaufort Sea Beluga Stock assessment meeting (Loseto et al., 2017 in review): Within the document recommendations of indicators for long term monitoring were proposed. Beluga condition indicators such as blubber thickness and girth were assessed along with stable isotopes and fatty acids (Choy et al., 2017 accepted). Preliminary analyses of time-series data (historical data combined with recent sampling) include assessment of three beluga health indicators (blubber thickness, girth, size at age, body mass index) including data variability, spatial differences, and confounding factors when assessing condition metrics.

b) Beluga Habitat and Habitat Use: Aerial survey data of belugas near the Mackenzie Estuary and in the Beaufort Sea offshore analyzed for beluga habitat use and indicator selection (Hornby et al., 2016; Hornby et al., 2017 accepted). Analysis of Kugmallit Bay seafloor habitat completed, manuscript in preparation (Whalen et al., in prep). Multivariate analysis to be performed to assess the degree to which environmental variables influence beluga presence, also analyzing differences in usage patterns at different mooring sites. Further analysis of extreme forcing events from 2016 are on-going and will provide a better understanding of how wind, waves and beluga whales interact in the bay during stormy conditions.

c) Fish Niche Assessment-Shingle Point Case Study: Diets and habitat of 16 fish species in the Tarium Niryutait Marine Protected Area (TN MPA) provides a baseline from which to assess against. Also, the characterization of these fish niches will be used for the selection of key species for long term monitoring at Shingle Point (in the TN MPA).

Communication: All western science indicators results were presented at ArcticNet ASM, the Beaufort Sea Partnership meeting (Inuvik 2016), DFO, and IGC meetings. Beluga related indicators were presented at the Inupiat-Inuvialuit Beluga Whale commission meeting (Edmonton 2016), the Beluga whale health workshop (Anchorage 2016) and co-management board presentations. Fish Niche Assessment results have been published (Brewster et al., 2016) and submitted (Brewster et al., 2017 in review).

3. Regional Scale Marine Indicators and Monitoring

This includes Management and Community Objectives Assessment and Prioritization, Ecosystem level Indicators, and Indicator Database Development.

Community consultation meetings: Researchers have consulted with IGC, FJMC, IRC, and DFO at various stages of project development (2015-2017). HTC meetings in Inuvik, Tuktoyaktuk and Community Corporation meeting in Tuktoyaktuk and Ulukhaktok have occurred in early development stages for feedback (2015). Presentations to Beaufort Sea Partnership (BSP) (2015, 2016) and collaborations to prioritize stakeholder objectives. Consultations with IGC, FJMC, IRC, ENR, Parks, DFO to identify datasets being collected in the ISR as contributions to regional database on indicators.

Data Collection

a) Management and Community Objectives Assessment and Prioritization: Previously identified management objectives for monitoring (year 1) are being compared to community priorities. Preparation for upcoming community tour to identify community priorities for monitoring. This includes interviews for the six Inuvialuit communities to assess the state of marine monitoring and to identify if current programs are capturing community needs.

b) Ecosystem Level Indicators: Data for biomarkers in species is based on projects listed under "Western Science Indicator Development" and other published papers. Collection of data to complete the Ecosystem (Ecopath with Ecosim: EwE) Beaufort Sea Shelf model was collected prior to the ArcticNet project.

c) Indicator Database Development: Development of a regional database of social, ecological, and economic indicators to provide an overview of monitoring activities in the ISR and the datasets being collected alongside them.

Data analysis and synthesis

a) Management and Community Objectives Assessment and Prioritization: Analysis of management objectives for monitoring were prioritized with the assistance of the BSP (Hoover et al., in prep-a). Analysis for community priorities expected in 2018.

b) Ecosystem Level Indicators: An existing Ecopath with Ecosim (EwE) food web model for the Beaufort Sea Shelf was used to compare against biomarker (stable isotope) data to strengthen understanding of the food web. We also identify keystone species as an approach to consider indicator species (Hoover 2013; Suprenaud and Hoover, submitted). This analysis will highlight strengths and weaknesses in each approach and our understanding of the food web.

c) Indicator Database Development: To data over 400 datasets have been identified and inventoried across the region, with another 200+ noted as existing for future incorporation. Information on each dataset includes: Project name, indicator information, various data metrics and contact/ links to retrieve data.

Communication: Presentations back to IGC (Whitehorse Sept 2016), FJMC (Jan 2017), and individual correspondence with IRC and DFO regarding the data and updates of the database. Report to the Beaufort Sea Partnership in addition to presentation at the annual meeting (Inuvik October 2016) to provide updates. Presentation at ArcticNet

ASM (Winnipeg 2016). Manuscripts: Suprenaud and Hoover (Arctic Science: submitted), Hoover in (prep-b).

RESULTS

1. Local Scale Beluga Indicators

a) LEK/TEK Indicator Development: Community experts identified indications such as swimming behaviour, physical shape of the whale, and wounds followed by blubber thickness and quality, meat quantity and quality, and appearance of internal organs. Indicators were evaluated based on ability to be recorded (by harvesters, monitors, community members), and the importance of the observation by community members based on consensual informant responses or key informant responses. Inuvialuit knowledge of beluga calving areas, potential nursery areas, feeding areas and travel routes/times in the areas surrounding the communities of Tuktoyaktuk, Paulatuk and Ulukhaktok, and harvest sites (East Whitefish, Kendall Island and Hendrickson Island) provides unique and significant information to support the monitoring of beluga habitat use in these coastal areas (Ostertag et al., in prep).

b) Traditional Ecological Knowledge of Beluga and Change: Changes in environmental conditions and beluga behaviour in Tuktoyaktuk are being observed on an ongoing basis, including changes in sea ice dynamics, seasonal temperatures, wind, and the frequency and intensity of extreme weather events. Inuvialuit appear to be coping with these changes thus far, continually updating and modifying their knowledge on beluga in light of new observations and experiences and fall into the following categories: TEK of Beluga Behaviour/Ecology, Hunting Techniques, Subsistence Food Preparation, Values and Observations of Change.

2. Western Science Indicator Development

a) Beluga Health: Beluga health monitoring assesses condition, diet indicators, diseases, contaminants, hormone and vitamin levels. Necropsies show overall good' body condition despite some thin animals, a few internal organ abnormalities, and some parasites. Blubber thickness and girth measurements (condition metrics: Choy et al., 2017 accepted) will be expanded to determine long-term changes in beluga health.

b) Beluga Habitat and Habitat Use: For habitat use of the Beaufort Sea shelf, beluga locations from spring (2012-2013) and late-summer (2007-2009) aerial surveys combined with environmental variables suggest that the Shallow Bay and the ice edge (where increased freshwater and nutrients were present), may provide key habitat variables for beluga before break-up (Hornby et al., 2016). Changes in break-up date (Hornby et al., 2014, Hoover et al., 2016), have altered arrival time (D. Whalen, NRCan Dartmouth, NS, pers. comm., Swainson pers. comm., Gordon pers. comm.). Habitat use in the estuary is likely impacted by type of benthic habitat and other environment factors such as tides, temperature, salinity and storms (Whalen et al., in prep).

c) Fish Niche Assessment: Shingle Point, Case Study: Fish diet biomarkers (stable isotopes and fatty acids) distinguished several key fish groups from which niche (diet and habitat) assessments were completed (Brewster et al., 2016). Fish groups (coastal, marine, benthic) are identified based on feeding and habitat, and can be used to select appropriate indicator species for long term monitoring at this location.

3. Regional Scale Marine Indicators and Monitoring

a) Management and Community Objectives Assessment and Prioritization: Previously identified management objectives and priorities (year 1) will be compared against community priorities on upcoming tour to provide a balanced perspective across the ISR. Community interview questions will focus on: (1) What community members feel is important to monitor in the marine environment, (2) If certain monitoring activities are more important that others (Priority monitoring activities), and (3) How different aspects of the marine ecosystem or environment are related to the key monitoring activity, to help identify high-priority monitoring programs, and any research gaps.

b) Ecopath with Ecosim Model and Biomarker Indicators: The Ecopath with Ecosim (EwE) model for the Beaufort Sea shelf (coastal area < 200m depth) identifies trophic structure using dietary linkages between species and includes harvest levels and environmental drivers. Here, all species or species groups can be compared in a systematic manner to identify unique (or keystone) species from the ecosystem model perspective. Figure 1 identifies species with values close to 0 as having a higher keystone value; a high relative total impact on the food web relative to its biomass (Power et al., 1996, Heymans et al., 2012). Comparison of the EwE model with over 630 records of biomarker (stable isotope) data for the region show positive correlations using different methods of calculating trophic level (Figure 2). This demonstrates our collective understanding of ecosystem structure using different approaches.

c) Regional Database of Indicators: Compiling management datasets is occurring in multiple iterations. After consulting with federal, territorial, and local management agencies and representatives, datasets are inventoried into the database (Table 1). During the Fall 2016, datasets were identified from IRC, ENR (Environment and Natural Resources), FJMC, DFO, and Parks Canada. EISC, EIRB, and IGC were consulted, but acknowledged they did not have their own datasets to contribute. During the next year we will continue to incorporate datasets from territorial governments (GNWT, GY) and federal government agency AANDC/ INAC if they have any datasets to contribute.

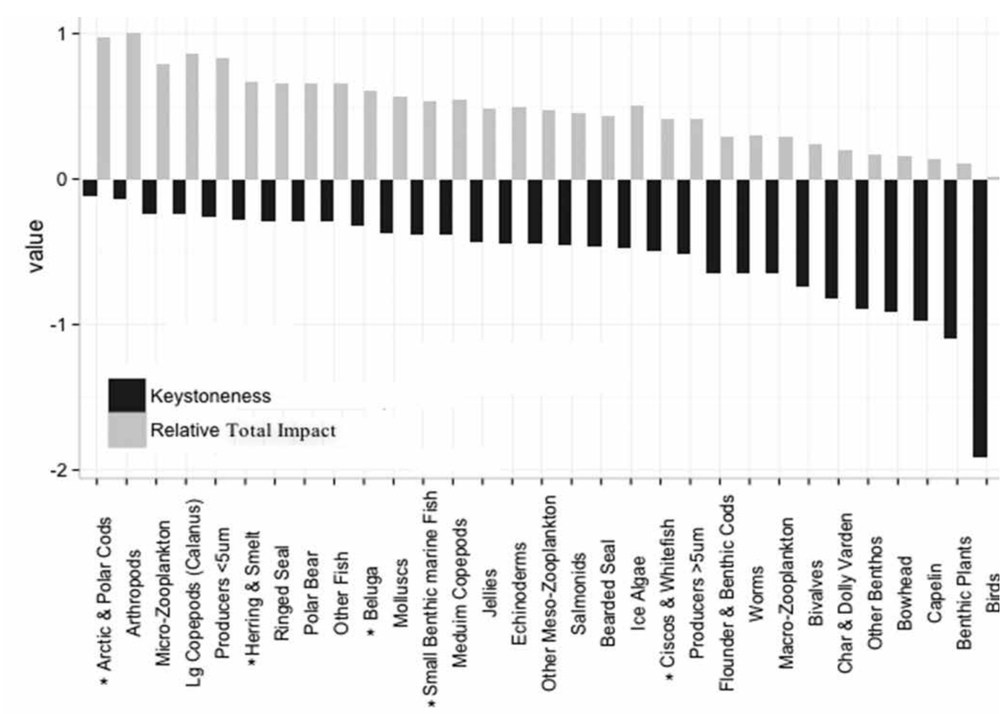

Figure 1. Keystoneness index and Relative Total Impact for species and species groups within the ecosystem model. Beluga prey species are noted with an asterisk (*).Values presented are updated from Hoover (2013), Hoover et al. (in prep-B).

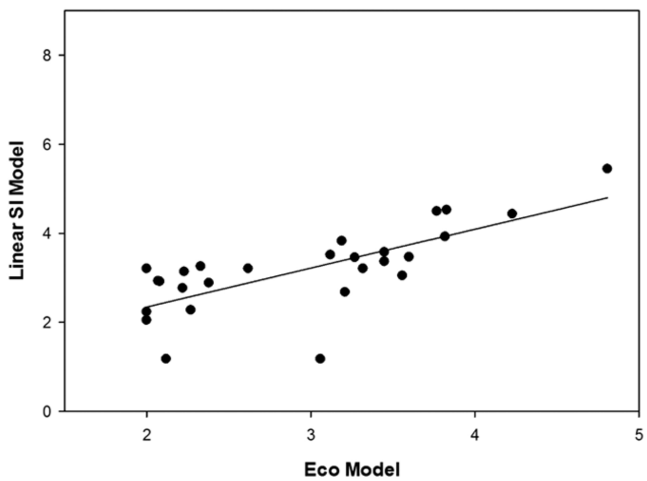

Figure 2. Relationship between the trophic level calculated with the Ecopath Model (EcoModel) and the stable isotope values derived using the linear method Linear SI Model (Post 2002). The solid line is a linear regression (R2 = 0.75, p < 0.0001).

Table 1. Summary of datasets contributing to the Indicators database and stage of completion. Agencies consulted include: DFO, FJMC, ENR, IRC, AANDC/INAC (Aboriginal Affairs and Northern Development Canada/ Indian and Northern Affairs Canada), GNWT (Government of the Northwest Territories), GY (Government of Yukon), CWS/ EC (Canadian Wildlife Service/ Environment Canada). In progress means consultations and/ or data integration has begun, with more than half of intended agencies as participants. Number of indicators shows the number of indicator or long-term datasets catalogued on behalf of each agency.

Agency	Status	Number of Indicator or Long-term Datasets
DFO- Science	In progress	~200
DFO- Oceans	In progress	TBD
FJMC	In progress	(Fall under DFO –Science)
ENR	In progress	23
IRC	No direct contributions	~360
WMAC (NS, NWT)	In progress	TBD
EISC, EIRB	No direct contributions	0
Parks Canada	In progress	5-10
IGC	No direct Contributions	0
AANDC/INAC	Start in 2017	TBD
GNWT	Start in 2017	TBD
GY	Start in 2017	TBD
CWS/ EC	Start in 2017	TBD
Total Minimum Datasets		588

DISCUSSION

Local Scale

- LEK/TEK indicator development: Beluga health is characterized from an Inuvialuit perspective in the context of beluga as an important food resource. Therefore, harvested belugas are typically healthy and their health is defined largely by the quantity and quality of the animal's muktuk, blubber and muscle, which are the primary organs utilized today for food. Examples of how the scientific community monitors beluga health includes the study of infectious disease, lesions/neoplasms/tumours, reproductive success/ complications, blubber thickness, growth rates/ age at growth, indicators of stress, exposure to contaminants and toxicological endpoints (Harwood et al., 2015; Desforges et al., 2013; Loseto et al., 2015; Ostertag et al., 2013, 2014; Pleskach et al., 2016). Scientific studies often require scientific expertise onsite to collect samples or conduct a thorough necropsy of dead animals, which would be logistically and economically unfeasible for all harvested whales. The study of beluga health from an Inuvialuit perspective adds value to beluga monitoring in part by providing a long-term perspective on beluga health based on generations of harvesting activities (McGhee, 1998) and by providing in-depth knowledge about the overall health of each harvested whale.
- Local observations and TEK about beluga habitat use reflect observations made during the everyday activities of community members in addition to specific beluga harvesting activities. In the Mackenzie Delta and Darnley Bay, the Inuvialuit residing in coastal communities or camping at coastal harvest camps observe beluga throughout the summer and fall (June to November) while travelling, fishing, spending time outside and harvesting beluga. The observations made by Inuvialuit TEK holders in this area reflect a long history of observing beluga and inter-

generational transmission of knowledge about beluga habitat use. Beluga habitat use in the Inuvialuit Settlement Region has been recorded and characterized by scientists by recording vocalizations (Simard et al., 2014), aerial surveys (Hornby et al., 2014, 2016; Harwood et al., 2014) satellite tagging (Hauser et al., 2015) and the analysis of relationships between environmental variables and habitat use (Simard et al., 2014; Hornby et al., 2014, 2016). Beluga distributions and subsequent habitat selection may already be changing over space and time. By incorporating aerial survey methods with habitat analysis, the relationships between beluga and the habitats they occupy can be examined at a finer scale. These habitat-relationships enhance our baseline from which to study the effects of climate change and inform future monitoring program.

- Observations made by the Inuvialuit have the potential to expand the spatial and temporal scale of recorded beluga habitat use. In addition, TEK provides a historical context to present day beluga sightings and changes being observed in the ISR. Traditional Ecological Knowledge also supports the development of research questions and methods in response to environmental changes occurring in the ISR. The Beluga Summit offered the first venue of its kind to bring together knowledge holders from different expertise and knowledge centers together in one northern location to share and co-produce knowledge. The framework is in development and central to the framework will be to identify gaps and set forward direction for future research in support of decision-making and the long-term viability of this beluga population.

Regional Scale

- Ecological indicator evaluation: In order to select meaningful indicators for monitoring programs, clear objectives are needed to direct management (Rice and Rochet 2005). Based on our assessment of objectives, there is a disproportionate amount of broad non-measurable objectives for marine monitoring, which makes future indicator selection potentially difficult. Nearly 2/3 of regional objectives are currently non-measurable (without further work), meaning changes to initial objective have the potential to streamline monitoring programs and make them more focused on priorities, rather than attempting to capture all possible changes in the system. Because this project is occurring in real-time along with the development of MPA (Marine Protected Area) monitoring goals, there is the potential to work alongside DFO partners to develop more tangible goals for future programs. With respect to the remaining co-management agencies, the research team hopes to provide recommendations regarding objectives to support future updates to monitoring programs regarding indicators.
- Current research activities revolve around data analysis at multiple levels, but all follow the same general protocol of building datasets around a common goal or objective and finding the best datasets that capture tends or changes, and confirming their relevance to the original goal or objective. Using the Beluga Health indicators, multiple datasets are being amassed and analyzed in varying capacities in order to identify changes in the local beluga population and the drivers of these changes. This has previously been identified as a priority for communities (see local ecological indicators section), and management (TN MPA management plan: DFO 2013). High quality indicator dataset will have to demonstrate their capacity to capture changes (trends) to be useful as an indicator. Because these have already been identified by management and communities, they already fit the criteria of relevance to a specific goal or objective.
- The complementary perspective of community priorities for monitoring will serve to provide a balance to the management perspective in the event the two perspective do not align. These together will be used to assess indicators currently being used in the region as collected

by the regional database of indicators. As multiple smaller components under this project (Ecosystem model, SI, LEK indicators) feed into this to increase our understanding of ecosystem changes, moving forward, the entirety of indicators (from the central database) will be assessed based on different goals; management, community, or a combination of both. The legacy of this program will be to provide scientists, co-management agencies, and HTCs will a comprehensive perspective of management goals and community goals for monitoring to be compared to available data. Priority goals from either side with no available data should trigger managers to strongly consider why programs do not exist. Conversely, if managers acknowledge funding multiple projects with similar data collection protocols for alignment of research should be implemented.

CONCLUSION

The Arctic marine ecosystem is undergoing rapid change under new climatic conditions with implications for marine biota and the human communities who depend on them for their livelihoods. There is a vested interest among Inuvialuit, Inuit and other decision makers to monitor these changes to inform management practices. Indicators are useful for characterizing ecosystems in measurable terms that can be monitored for management purposes but objectives and targets must be clearly defined for setting management priorities in order for indicators to be relevant. To date little incorporation of LEK and TEK has been used in the development of indicators for ecosystem monitoring. Moreover, Inuit have a highly detailed and holistic understanding of the marine ecosystem, which taken together with western scientific understanding can develop more robust and accurate indicators and monitoring programs. This research program has taken several approaches to collect LEK/TEK to support indicator selection as well move toward a co-production approach to indicator identification at local and regional levels. Our research program has and continues to bridge Inuvialuit knowledge and western scientific knowledge through the co-production at two scales, one at the local scale focused on knowledge related to beluga whales and two at the regional scale to identify relevant indicators to monitor and measure changes in the Beaufort Sea ecosystem.

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