ArcticNet **ᐅᑭᐅᖅᑕᖅᑐᕐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ**

Impacts of Environmental Change in the Canadian Coastal Arctic

A Compendium of Research Conducted during ArcticNet Phase IV (2017–18)

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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 ᑐᑭᓯᓂᐊᖅᑎᒌᑦ ᐃᓂᖃᖅᑎᑕᐅᔪᖅ ᓚᕚ, ᑯᐸᒃ ᓯᑎ, ᑲᓇᑕ

ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖅᑎᒌᑦ ᐱᑕᖃᕈᓐᓇᖅᑎᑕᐅᔪᖅ ᑳᒃᑯᓐᓇᙵᑦ ᑮᓇᐅᔭᒃᓴᖅᖃᖅᑎᑕᐅᓪᓗᓂ ᑐᑭᓯᒐᓱᐊᖅᑎᒌᑦ ᐱᑐᒃᓯᒪᓂᒃᑯᑦ ᑐᑭᓯᓐᓂᐊᖅᑎᒌᑦ ᐱᐅᓛᑦ ᑲᓇᑕᒥ, ᑲᑐᑎᔭᐅᓪᓗᓂ ᐱᓕᕆᐊᕆᔭᐅᔪᖅ ᑳᒃᑯᓐᓇᙵᑦ ᓄᓇᒥᐅᑕᕐᓂᒃ ᖃᐅᔨᓴᐃᔨᒻᒪᕆᑦ ᐊᒻᒪᓗ ᐃᑯᒪᓕᕆᓂᕐᒥ ᖃᐅᔨᓴᖅᑎᑦ ᑲᑎᒪᔨᖏᑦ, ᑲᓇᑕᒥ ᐃᓕᓐᓂᐊᕐᕕᒃ ᐃᓅᓯᓕᕆᓂᕐᒥ ᖃᐅᔨᓴᐃᓂᖅ, ᐃᓅᓯᕐᒥ ᖃᐅᔨᓴᐃᓂᒻᒪᕆᒃ ᐊᒻᒪᓗ ᐃᓅᔾᔪᑎᕆᔪᓐᓇᖅᑕᑦᑎᒍᑦ ᖃᐅᔨᓴᐃᓂᖅ ᑲᑎᒪᔨᖏᑦ, ᐊᒻᒪᓗ ᐱᓇᓱᐊᖅᑐᓕᕆᓂᖅ ᑲᓇᑕ.

ᐅᑯᐊ ᐱᑐᒃᓯᒪᕖᑦ ᐱᐅᓛᑦ ᑲᓇᑕᒥ ᐊᔾᔨᐅᙱᑑᔪᒥᒃ ᐱᓇᓱᐊᖅᑎᒋᔭᙵᑦ ᐊᕙᑖᓂᑦ ᐃᓚᓐᓂᐊᕐᕕᒃᔪᐊᓂ, ᐱᓇᓱᐊᖅᑐᓕᕆᓂᖅ ᑲᓇᑕ, ᒐᕙᒪᒃᑯᑦ ᐊᒻᒪᓗ ᑮᓇᐅᔭᓕᐅᕋᓯᐊᕋᑎᒃ ᐊᐅᓚᑦᓯᔨᐅᔪᑦ ᑐᕌᖅᑐᑦ ᑐᓄᑎᒍᓐᓇᖅᓱᒍ ᑲᓇᑕᒥᐅᑦ ᖃᐅᔨᓴᖅᓂᙵᑦ ᐊᒻᒪ ᓇᖕᒥᓂᖅᖃᖅᑐᓕᕆᓂᖅ ᐱᓕᕆᔪᓐᓇᑦᓯᐊᖅᑐᑦ ᑕᒪᑐᒧᙵ ᒪᑭᑕᓇᓱᐊᕐᓂᕐᒧᑦ ᐊᒻᒪᓗ ᐃᓅᓯᕐᒥ ᐃᑲᔫᑎᓂᐊᖅᑐᓄᑦ ᑕᒪᐃᓐᓄᑦ ᑲᓇᑕᒥᐅᓄᑦ. ᑕᐃᒪᓗ ᐃᓗᓪᓕᓴᓗᐋᖅᑕᖓ ᐃᓚᖓ ᒐᕙᒪᑐᖅᑲᒃᑯᑦ ᓄᑖᓂᒃ ᐱᕆᐊᓪᓚᒍᑎᓕᓴᓂᖅ ᐋᖅᑭᒃᓯᒪᐅᑎᖓᑦ, ᐅᑯᐊ ᑲᓇᑕᓕᒫᒧᑦ, ᐊᒥᓱᑦ ᐃᓂᖅᑎᕆᔪᓐᓇᖅᑐᑦ ᐊᒻᒪᓗ ᐊᒥᓱᑦ ᖃᓄᑐᐃᓐᓇᖅ ᐱᓕᕆᔪᓐᓇᖅᑕᓖᑦ ᑲᑎᙵᔪᑦ ᐱᐅᓂᕐᐹᙳᔪᒥᒃ ᖃᐅᔨᓴᐃᓂᕐᒥᒃ ᐱᓇᓱᐊᖅᑐᓕᕆᓂᕐᒥ ᖃᐅᔨᓴᖅᑕᐅᓕᕈᓐᓇᖅᑐᓂᒃ ᐊᒻᒪᓗ ᐋᖅᑭᒃᓯᒪᐅᑎᖓᑦ ᖃᑭᓚᓯᐊᕈᑎᒋᔪᓐᓇᖅᑐᓂᒃ.

ᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖅᑎᒌᑦ ᐱᑐᒃᓯᒪᖅᑎᒋᔭᙱᑦ ᑳᒃᑯᓐᓇᙵᑦ ᑐᑭᓯᒐᓱᐊᖅᑎᒌᑦ ᐱᑐᒃᓯᒪᓂᒃᑯᑦ ᐱᐅᓃᑦ ᑲᓇᑕᒥ ᑎᒥᙳᖅᑎᑕᐅᓯᒪᔪᑦ ᑮᓇᐅᔭᓕᐅᖅᑎᐅᓚᓯᐊᕋᑎᒃ ᑯᐊᐳᓴᓐ ᐊᑖᒍᑦ ᐊᑎᖅᖁᑎᒃ “ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖅᑎᒌᒌᑦ ᑎᒥᙵ” ᑕᐃᑲᓂ ᑎᓯᐱᕆ 2003.

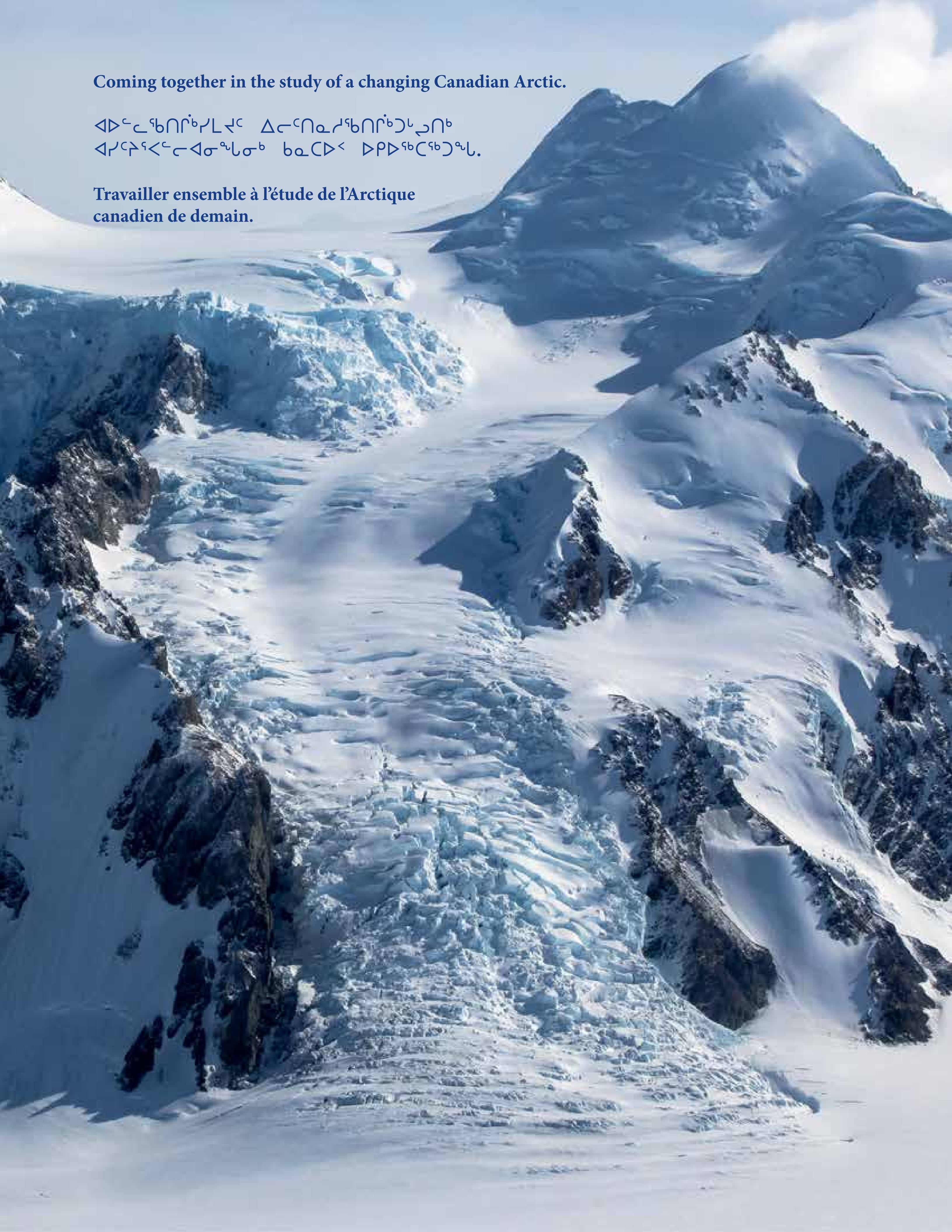
Le centre administratif d’ArcticNet se situe à l’Université Laval, Québec, Québec, Canada.

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.

**ᐊᐅᓪᓚᖅᑎᒌᒃᓯᒪᔪᑦ ᐃᓕᑦᑎᓇᓱᖅᑎᒌᒃᑐᒡᓗᑎᒃ
ᐊᓯᑦᕋᕐᐸᓪᓕᐊᓂᖓᓂᒃ 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 third year of phase IV (2017-2018) 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

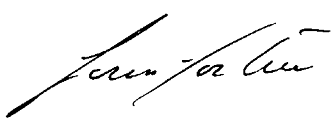
ᐅᓇ ᐅᑭᐅᖅᑕᖅᑐᖅ ᓄᓇᕗᑦ ᓄᓇᕐᔪᐊᒥ ᐊᒃᑐᖅᑕᐅᖃᕐᓂᐊᖅᑐᖅ ᐊᒻᒪᓗ ᐊᖏᓛᖑᔪᒥᒃ ᓱᑯᑕᐅᓗᓂ ᑕᒪᑐᒪᖓᑦ ᓂᒋᐊᓂᒐᖅᑐᓂᑦ ᐅᖅᑰᓯᐋᓪᓕᐊᓂᖓᓄᑦ ᓄᓇᕐᔪᐊᑦ. ᐅᓄᖅᑐᑦ ᑕᒪᔾᔭᐅᓕᖅᑐᑦ ᖃᐅᔨᑎᑦᑎᔪᑦ ᐅᑭᐅᖅᑕᖅᑐᖅ ᐅᖁᓯᓂᖓᓄᑦ ᖃᐅᔩᔾᔪᑎᖃᖅᖢᑎᒃ ᓯᓚᐅᑉ ᖃᓄᐃᓐᓂᖓᓂᒃ ᓴᓇᕿᑕᐅᔪᓂᒃ ᓇ, ᓇᐃᖅᑐᖅ ᑕᑯᔭᐅᔪᖅ ᓄᓇᑐᐃᓐᓇᒥ, ᑕᕆᐅᕐᒥ ᐊᒻᒪᓗ ᓄᓇᕐᔪᐊ ᓯᓚᑖᓂ. ᓇᐃᓈᖅᑐᒍ ᐅᖃᕈᓐᓇᖅᑐᒍᑦ ᐅᑭᐅᖅᑕᖅᑐᖅ ᓯᓚᒐᑕ ᐊᕙᑎᖓᑕ ᐊᓯᑦᑐᕐᓂᖓ ᐊᒃᑐᖅᑕᐅᓂᖓᓂᒃ ᓱᕐᑯᐃᖅᑕᐅᓇᓱᒃᓯᒪᔪᓂᑦ 2004, ᐊᒥᓱᑦ ᐊᔾᔨᒌᙱᑦᑐᑦ ᓯᓚᖕᓂᐊᖅᑐᑦ, ᐃᓅᓯᓕᕆᓂᕐᒥᒃ ᑮᓇᐅᔭᑎᒍᑦ ᐱᕙᓪᓕᐊᓂᖅ ᐊᒻᒪᓗ ᓄᓇᖕᒥᓐᓄᑦ ᓚᕙᓕᕆᓂᖅ ᑕᒪᔾᔭ ᐱᓕᕆᔭᐅᔪᑦ ᐅᑭᐅᖅᑕᖅᑐᒥ ᑕᐃᒪᓗ ᐊᓯᑦᑏᓂᐊᖅᑐᖅ ᑭᓱᖑᕐᓗᓂ ᐅᑎᕈᓐᓇᕐᓂᐊᙱᑦᑐᖅ ᐅᑭᐅᖅᑕᖅᑐᒥ ᑕᐃᒪᓐᓇᐅᖏᓐᓇᐅᔭᓕᕐᓂᐊᖅᑐᑦ. ᐅᑭᐅᖅᑕᖅᑐᒥ ᑐᑭᓯᓐᓂᐊᖅᑲᑎᒌᑦ ᓄᐊᑎᓇᔪᑦ ᖃᐅᔨᒪᔭᐅᔪᓂᒃ ᐊᒻᒪᓗ ᓱᕐᑯᐃᖅᑕᐅᓯᒪᔪᓂᒃ ᑭᙴᒪᒋᔭᐅᓯᒪᔪᓂᒃ ᐋᖅᑭᒃᓯᓂᐊᖅᖢᑎᒃ ᓱᖕᕆᐅᑎᑦᑎᔾᔪᑎᒃᓴᐃᑦ ᐊᒻᒪᓗ ᐊᑐᐊᓚᐃᑦ ᐅᑯᐊ ᐃᑲᔪᕐᓂᐊᖅᑐᖅ ᐅᑭᐅᖅᑕᖅᑐᒥᐅᓂᒃ ᐊᒻᒪᓗ ᑲᒻᐸᓂᐅᔪᓂᒃ ᐱᓂᒃᓴᕇᖅᓯᒪᓗᑎᒃ ᐊᒃᑐᖅᑕᐅᓂᖓᕐᓂᖓᓄᑦ ᐊᕙᑎᖓᑦ ᐊᒻᒪᓗ ᐃᓅᓯᖏᑦ ᐊᓯᑦᑏᕐᓗᑎᒃ ᓯᓪᔭᖏᑦ ᑲᓇᑕᐅᑉ ᐅᑭᐅᖅᑕᖅᑐᐊᓂ. ᐅᓇ ᑕᐅᑦᑐᓇᔭᕗᑦ ᓴᓇᓗᒍ ᓯᕗᓂᒃᓴᕗᑦ, ᖁᔭᓐᓇᒦᒃ ᑕᒪᔾᔭᐅᕐᒪᑦ ᑐᓴᐅᒪᖅᑲᑎᒌᖕᓂᖅ ᖃᐅᔨᒪᖅᑲᑎᒌᖕᓂᖅ, ᒥᐊᓂᕆᓂᖅ, ᐋᖅᑭᒃᓱᐃᓂᖅ ᐊᒻᒪᓗ ᐃᓗᓪᓕᖅᓱᐃᓂᖅ, ᖃᐅᔨᓴᖅᑎᒻᒪᕇᑦ ᐊᒻᒪᓗ ᐅᑭᐅᖅᑕᖅᑐᒥᐅᑦ ᑲᑎᓯᒪᔭᖕᕆᓐᓂᑦ ᐱᓕᕆᑦᑎᐊᖅᖢᒋᑦ ᐱᐅᓐᖏᓪᓗᑎᒃ ᐊᒃᑐᐃᓇᔭᓚᐅᖅᑐᓄᑦ ᐊᒻᒪᓗ ᐊᖏᓪᓕᑎᓯᒪᓪᓗᒋᑦ ᐱᐅᔪᓂᒃ ᐊᑑᑎᖃᑦᑎᐊᖅᑐᓂᒃ ᐱᓪᓗᒍ ᑕᒪᓐᓇ ᐊᓯᑦᑏᕐᓂᖅ. ᑭᓲᓂᖏᑦ ᐱᑕᖃᖅᑐᑦ ᐅᑯᐊ ᓯᕗᓪᓕᕐᒫᑦ ᐱᓕᕆᔭᐅᔪᑦ ᑕᒪᑐᒧᖓ ᑕᕐᑯᔭᐅᓯᒪᔪᓂᑦ ᑲᔪᓯᑦᑎᐊᖅᓯᒪᔪᑦ ᓯᕗᓪᓕᕐᓂ ᐊᕐᕋᒍᓂ ᑎᓴᒪᓂ (ᓱᕐᕌᓂᖓ 1) ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓐᓂᐊᖅᑲᑎᒌᑦ. ᖁᔭᓐᓇᒦᒃ ᑕᒪᑦᓯ ᑐᑭᓯᓇᓱᐊᖅᑲᑎᒌᑦ ᖃᐅᔨᓴᖅᑎᑦ, ᐃᓕᓐᓂᐊᖅᑐᑦ, ᐊᓯᖕᒥᓪᓗ ᖃᐅᔨᓴᖅᑎᑦ, ᓴᓇᖅᑲᑎᒋᔭᕗᑦ ᐊᒻᒪᓗ ᐱᓇᓱᐊᖅᑲᑎᒋᔭᕗᑦ ᐃᑲᔪᖅᑐᑦ ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓐᓂᐊᖅᑲᑎᒌᒃᑯᓄᑦ ᑲᔪᓯᑦᑎᐊᖅᑎᑦᑐᒋᑦ, ᐊᒻᒪᓗ ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓐᓂᐊᖅᑲᑎᒌᑦ ᑭᓲᓂᖏᓐᓂᒃ ᑎᑎᖅᑲᑎᖏᑦ ᐱᓇᓱᐊᖅᑲᑎᒌᓚᐅᖅᑐᑦ ᐅᓇ ᑎᑎᖅᑲᓯᒪᔪᖅ ᐱᔭᕇᑦᑎᐊᖅᓱᓪᓗᒍ.

ᐃᓕᓴᐃᔩᓪᒪᕆᒃ ᒍᐃ ᑯᐊᑦᓯᔭᐃ, ᖃᐅᔨᓴᕐᓂᕐᒥᒃ ᑐᑭᒧᐊᒃᑎᑦᓯᔩ ᐅᑭᐅᖅᑕᖅᑐᕐᒥᒃ ᑐᑭᓯᓂᐊᖅᑲᑎᒌᒃᑯᓐᓂᑦ

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 troisième année (2017-2018) 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 and Carl Barrette

This Compendium of Research (2017–18) presents research progress of the third and final year of Phase IV ArcticNet projects, which ran from 1 April 2017 to 31 March 2018. Twenty-two projects were organized under five complementary research themes of Phase IV: 1) Marine systems (10 projects); 2) Terrestrial systems (6 projects); 3) Inuit health, education and adaptation (4 projects); 4) Northern policy and development (1 project); and 5) Knowledge transfer (1 project).

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.

2017-2018

ArcticNet has now completed its fourteenth year, and we can look back on an unmatched trans-sectoral program of 119 research projects providing a wealth of information about the Canadian Arctic; four Integrated Regional Impact Studies detailing the consequences of climate change with recommended adaptation strategies; and an unprecedented effort to integrate university and government northern research efforts in collaboration with Inuit partners.

As the NCE funding of ArcticNet ends in March 2018, many fear a rapid erosion of the remarkable coherence the Network has created among Arctic specialists in academia, the government, the North and internationally, as well as with the users of research results in Canada and abroad. Many also apprehend a return to the dark ages of the 1990's when university-based Arctic specialists had to piggy-back federal programs and logistics for want of a coordinated approach to the study of the Canadian Arctic by universities (Hutchinson et al., 2000). Since the dawn of modern research in the Canadian Arctic in the 1950's, investments have tended to shift from government-based research to university-based research. It could be argued that, relative to other countries, the consolidation of Arctic sciences in Canada has suffered from this alternation. Why should Canadian Arctic science be concentrated in either the universities or the government departments at a given time, and not in both sectors at the same time? Ending this counter-productive academia-departments pendulum would help build the coordination and synergy needed to form a credible national effort in a country with limited funding capacity and daunting international expectations to deliver on Arctic sciences. Finally, the long overdue research and training capacity in the North and by the North that is rightfully demanded by Inuit organizations and the Territories (Territorial Premiers, 2016) is needed to complete the research dimension of a new Canadian northern strategy.

Following the recommendations of the recent review of Canada's fundamental sciences (Naylor et al., 2017), the NCE program has cracked open the door to the possibility of renewing networks like ArcticNet beyond their 14-year limit through a new competition with a relatively modest budget ($75M over 5 years for new and old networks). ArcticNet will be proposing its continued vision of an integrated field of Canadian Arctic Sciences for the sustainable development of Canada's North based on the following strategic objectives:

1. **Broaden the Network for Canadian Arctic science and Northern knowledge**. Expand the geographic and cultural scope of ArcticNet from the maritime Arctic (Inuit Nunangat) to include the Yukon, the continental sectors of the NWT, Nunavut, the northern First Nations and Métis peoples; and expand the network to include

emerging centres of excellence in academia, the North, and the public and private sectors.

2. **Mobilize scientific information and northern expertise**. Advance a comprehensive approach for the complementary sharing of natural, health and social science information with northern knowledge and the expertise of Inuit, First Nations and Métis peoples. Expand the trans-sector (natural, social, health, adding engineering) research program that underpins the Integrated Regional Impact Studies (IRIS) and, in close collaboration with the Arctic Council Arctic Monitoring and Adaptation Program (AMAP), transform existing IRISes into dynamic web-based resources continuously updated online.
3. **Arctic research logistics**. Support an integrated approach to terrestrial logistics based on the successful model of Amundsen Science, and mobilize a second research icebreaker for Canada to answer the growing national and international demand for coastal and offshore access to the Arctic.
4. **Strengthen and encourage diverse partnerships.** Expand engagement with the private and philanthropic sectors in northern research and social development and seek greater collaboration with non-governmental organizations.
5. **Inuit and Northern College-led research and training programs.** Building on the ArcticNet Inuit partnership and the vision expressed by the Territorial Premiers, support the development of research and training capacity in the North; implementation of the National Inuit Strategy on Research; and promote Arctic science and northern knowledge for training and youth engagement.
6. **Northern health**. Support the improvement of physical and mental health in the Canadian North in close partnership with Inuit, First Nations, Métis, Territorial and Provincial health organizations.
7. **"Big Science" in the Canadian Arctic.** Provide the Canadian research community with the financial seeding and logistics capacity to participate in and take the leadership of large multi-national endeavours to study and monitor the changing Arctic in both Canadian and circum-polar contexts.

Again as in the late 1990's, Canadian Arctic science is at a crossroad and requires a new roadmap. ArcticNet will continue to explore all possible avenues for the funding and consolidation of university-based northern research with the overarching goal of providing a strong academic component to Canada's emerging new northern strategy. We thank the entire Canadian and international Arctic science community for your past and future support of our efforts.

Louis Fortier
Scientific Director

Leah Braithwaite
Executive Director

References

Hutchinson T. et al. 2000. From crisis to opportunity: rebuilding Canada's role in northern research. NSERC/SHRC.

Naylor et al. 2017. Canada's Fundamental Science Review. Investing in Canada's future. www.sciencereview.ca/eic/site/059.nsf/eng/home.

Territorial Premiers (Yukon, NWT and Nunavut), 2016. A Pan-Northern Approach to Science, 2016. www.anorthernvision.ca/PanNorthernScience.html.

SECTION I. MARINE SYSTEMS

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

REMOTE SENSING OF CANADA'S NEW ARCTIC FRONTIER

Project Team

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ABSTRACT

The objectives of this project are aligned with the targeted achievements of the Canada Excellence Research Chair on "Remote Sensing of Canada's New Arctic Frontier" to: (1) Augment in time and space the observation of arctic marine ecosystems by implementing new algorithms for the remote-sensing of phytoplankton, particulate matter, dissolved organic carbon and seawater optical properties in the surface layer of the Canadian Arctic Ocean, from which primary production, bacterial growth, and organic matter photo-oxidation will be derived; (2) Develop, validate, and implement the urgently-needed ecosystem models that will help anticipate the impacts of climate change and industrialization on the resources and services (fisheries, navigation, minerals, energy, tourism) provided now and in the near future by the ecosystems of the Canadian Arctic Ocean; (3) Adapt existing and future new observing technologies to the extreme conditions of the Arctic Ocean, with emphasis on the field deployment of Profiling Floats, Autonomous Underwater Vehicles, and Ocean Gliders, and on the use of optical sensors; (4) In collaboration with the Canadian Cryospheric Information Network (CCIN), Centre d'études nordiques (CEN) and other national and international partners, mesh the respective expertise of ArcticNet and GEOIDE, two pan-Canadian NCE, into the development of state-of-the-art geo-referenced data archiving systems that can be accessed online by scientific, industrial and government stakeholders to produce maps and analyses of the transforming Canadian Arctic.

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.
- Through the use of imaging technologies (IFCB, UVP, LOKI) we have developed algorithms that allowed identification of *Phaeocystis* bloom, which indicates the northward migration of more southern species.
- 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.

RESEARCH 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

Websites

- Takuvik Joint International Laboratory http://www.takuvik.ulaval.ca
- Chantier Arctique http://www.chantier-arctique.fr/en/index.php
- Green Edge http://www.greenedgeproject.info
- 2015 blog Green Edge https://greenedgeproject2015.wordpress.com/
- 2016 blog Green Edge http://greenedge-expeditions.com/
- CERC http://www.cerc-arctic.ulaval.ca

Education

- AOA Arctic Ocean Arctique http://www.aoa.education/en: Educational multimedia platform for secondary school-aged students. The website contains 13 capsules (web-documentaries) of 3-5 min in length, each of which are associated with educational modules (quizzes, interactive activities…) and pedagogical files.
- 24h de la Science 2015 in Québec City – theme: La lumière – 8/9 May 2015: Contributor: Jose Lagunas – students visited the Takuvik labs at Université Laval.
- 24h de la Science 2016 in Québec City – theme: L'écologie – 6/7 May 2016: Contributors: Blanche Saint-Béat, Arnaud Pourchez and Deborah Benkhort, activities in local primary and secondary schools in Québec City region (500 students).

- 24h de la Science 2017 in Québec City – theme : La science-fiction – 12/13 May 2017:
  - » Bar des sciences, La Korrigane – Organiser: Julie Sansoulet.
  - » School activities, Contributor: Frédéric Maps, Neufchatel secondary school (150 students).
  - » Visit to Takuvik labs, Contributors: José Lagunas, Eric Rehm, Guislain Bécu, Pierre-Luc Grondin, hands on applications using gliders, profiling floats, optical imaging systems.
  - » Québec City Aquarium, Contributors: Julie Sansoulet, Joannie Ferland: Virtual and augmented reality, undersea world of plankton (+500 participants).
- Teacher's day 51st CMOS Congress, "Arctic Ocean: A cold dive in the green", Contributors: Julie Sansoulet, Joannie Ferland, 6 June 2017, Toronto.
- Scientific presentations in schools:
  - » Stanislas (Québec, QC) – Research in the Arctic Ocean– November 2013.
  - » Lacanau (France) – Marine Food Web– November 2015.
  - » Rochebelle (Québec, QC) – Arctic ecosystems – May 2016.
  - » Fernand Seguin (Québec, QC) – Arctic ecosystems– May 2016.
  - » Chandler Saint-Joseph (QC) – Marine Food Web – April 2016.
  - » ÉPAQ, Grande-Rivière (QC) – Marine Food Web – April 2016.
  - » Inuksuit School (Qikiqtarjuaq, Nunavut) – more than 30 thematic activities about the Arctic, Spring 2015 and 2016.
  - » E-twinning school project, Camp de l'Ile, of ArcticNet (Canada), Marcel Babin, Director, Montreal (QC) – science day camp (summer 2017).
  - » École primaire Lestrat (Havre St-Pierre, QC) – Plankton at the heart of the marine food chain – October 2017 (Grade 3, 40 students).
  - » École secondaire Monseigneur Labrie (Havre-St Pierre, QC) - The importance of the spring phytoplankton bloom – October 2017 (Sec 3, 52 students).
- "In the Wake of an Icebreaker in the Arctic" - Educational multimedia project- May to October 2016:
  - » Direct feed from the research icebreaker CCGS *Amundsen* to five schools in Paris (France).
  - » Conference by Pierre Coupel and Pascaline Bourgain as part of Fête de la Science – October 13, 2016, Paris, France.

Organisation of Events

- Launch of the French Arctic Initiative: conference at Collège de France – June 2013 - 500 participants.
- Stopover of the schooner TARA in Québec – November 2013 at the Port of Québec and the Musée de la Civilisation (Québec):
  - » Visit of the TARA by local students and the general public.
  - » Projection of the film "Tara Oceans, voyage aux sources de la vie".
  - » Organisation of a series of conferences at the Musée de Civilisation (Québec) with Eric Karsenti, scientific director of the Tara Oceans expeditions (2009-2012) et co-director Tara Oceans Polar Circle expedition (2013), Romain Troublé, secretary general of Tara Expéditions, Emmanuel Boss, researcher at University of Maine (USA), Martin Fortier, executive director Takuvik Joint International Laboratory and member of the scientific committee of Tara Oceans Polar Circle and

Florent Dominé, researcher at Takuvik Joint International Laboratory (Université Laval-CNRS).

- Visit of the Brossier family, owner of the polar yacht VAGABOND - at the Musée de la Civilisation (Québec) – January 2014:
  - » Projection of the film Sur le grand océan blanc by Hugues de Rosières andVéronique Ovaldé.
  - » Discussion with the Brossier family.
- FACTS 2015 L'Arctique, sentinelle du réchauffement climatique - Octobre 2015 at the Musée de la Civilisation (Québec):
  - » Photo exhibition by Vincent Hilaire, D'un pôle à l'autre.
  - » Projection of a documentary about the polar yacht Vagabond Sous les étoiles du pôle by Hugues de Rosières.
  - » Projection of the documantary Inuit knowledge and climate change by Zacharias Kunuk and Ian Mauro.
  - » Public conférences by Takuvik researchers.
- Organisation of a Bar des sciences "Quel arctique pour 2100 ?" - Microbrasserie la Korrigane, Québec, 13 May 2017 – 125 participants.
- Visit of François Bernard, Owner of the sailboat ATKA - at the Musée de la Civilisation (Québec) – 30 May 2017.
- Projection of the film Capitaine de l'Utopie by Sarah Del Ben and discussion with the captain, François Bernard.
- 52 min documentary Arctic Bloom /À l'orée de la banquise:
  - » Public screening June 15, 2017 at Université Laval.
  - » Teaser: https://vimeo.com/200974130.
- Thirteen min documentary Inuit Belief and Hunting by Julie Desraic, Guilhelm Pouxviel, Julie Sansoulet, and Guillaume Weissenburger:
  - » Public screening June 15, 2017 at Université Laval.
- Let the Arctic green flow. Photo exposition at Arctic Change 2017 by Noé Sardat, Sharif Mirshak, Christian Sardet.

INTRODUCTION

In the Arctic Ocean (AO), as in most parts of the World Ocean, the phytoplankton spring bloom (PSB) provides a large fraction of the annual primary production (PP) and, more importantly, nearly all of the new PP exportable through the food chain and toward the bottom sediments. The Arctic spring bloom often develops around the edge of the seasonal ice zone (SIZ), lasting about three weeks at any given location. The SIZ is currently increasing in size and may cover the entire AO as soon as the 2030s. Therefore, one may expect ice edge blooms to cover a much larger area than they used to through a significant northward expansion. However, we currently do not know the fate of this possible 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, contributing to 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 long-term objective is to determine the fate of the PSB in a changing AO. The adaptation of autonomous platforms such as Bio-Argos floats and profiling gliders to Arctic conditions will provide us with valuable data for monitoring rapidly changing marine ecosystems in the Canadian Arctic.

ACTIVITIES

Ice camp activities spring 2015 and 2016

During the 2015 and 2016 field seasons, an ice camp was established 30 km from the community of Qikiqtarjuaq (67° 29.23N and 63° 38.00W; Figure 1) consisting of a Polarhaven tent and a wooden cabin built on a sledge. The international team of researchers and their scientific equipment were transported to the site daily by snowmobile and Qamutik until ice conditions became harzardous. In 2015, twenty different categories of measurements were conducted during nearly 50 days of full-station sampling between mid-April and mid-July. Forty-seven people participated in GreenEdge ice camp activities in 2015.

2016 field work was carried at the same location 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). In addition to the ice operations in 2016, as part of Work Package 7 (Local Knowledge) Qikiqtarjuaq hunters of varying ages were interviewed to get their opinion about the evolution of hunting and fishing practices over recent decades. In late May, three GreenEdge researchers accompanied 12 Inuit to a hunting camp, acquiring first-hand knowledge about the impact of ongoing climate change on their traditional hunting territory. The process was repeated in Pangnirtung and Clyde River in 2017. All of the interviews were documented by a film crew and integrated into a short film entitled Inuit Belief and Hunting. A full length, 52-minute documentary about the GreenEdge project, Arctic Bloom, was produced by Parafilms and released in August 2017.

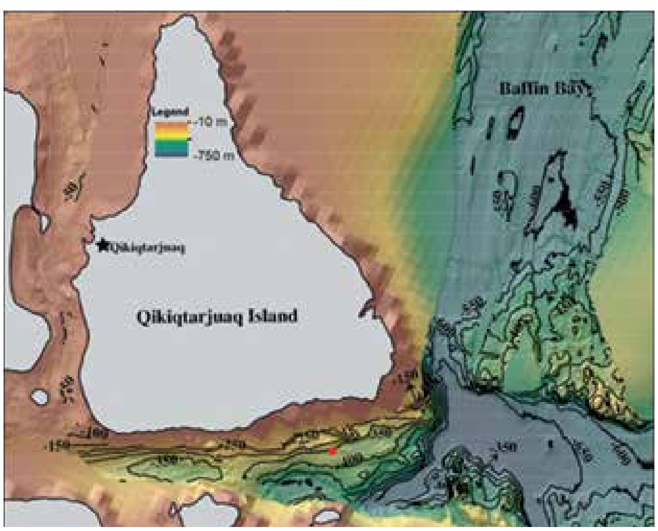


Figure 1. Map showing the location of the ice camp (red dot) south of Broughton Island 67˚28.784N, 063˚47.372W). Bathymetric data is from the high resolution multibeam echosounder installed aboard the CCGS Amundsen (credit: Gabriel Joyal and Patrick Lajeunesse) and the International Bathymetric Chart of the Arctic Ocean (IBCAO).

Operations conducted in the tent:

- CTD-Underwater Vision Profiler (UVP)
- Seawater sampling with 8 and 20L Niskin bottles at 6 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
- Monitoring of a 13-hour tidal cycle on June 23, 2016 using a CTD, BB3 and SCAMP

The following operations were conducted in the wooden cabin:

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

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
- Under ice incubations (production)
- Imaging and measurement of under ice light with a ROV and a cosine camera (2016 only)
- Measurement of snow optical properties
- Sediment traps
- Temporal series of images using a drone
- Meteorological station measurements

Real-time continuous measurements of sea ice mass balance with an Ice-T Buoy (2015 only)

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)
- Filtration (Ap, CHN/SPM, CDOM, Silice, genetic, sugar)

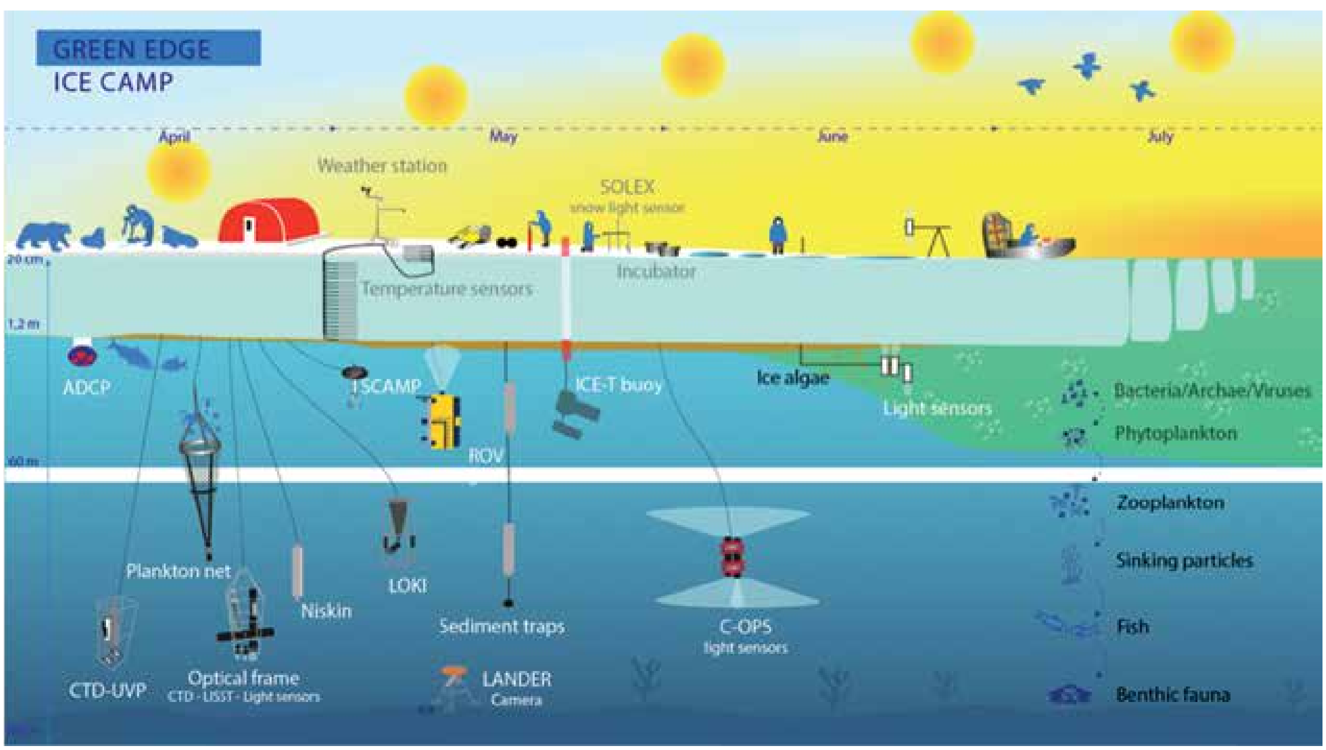


Figure 2. Visual summary of the instruments used during GreenEdge ice camp operations in 2016 (credit: Julie Sansoulet).

- Salinity ice cores
- Conservation of samples (freezing, refrigeration).

A visual summary of the on-ice operations conducted outside of the Polar Haven tent and wooden cabin is provided in Figure 2.

2016 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
- 26 SCAMP deployments

Continuous measurements:

- Geographic location of ship
- Met tower data, irradiance, total energy
- 360° time lapse photos around ship

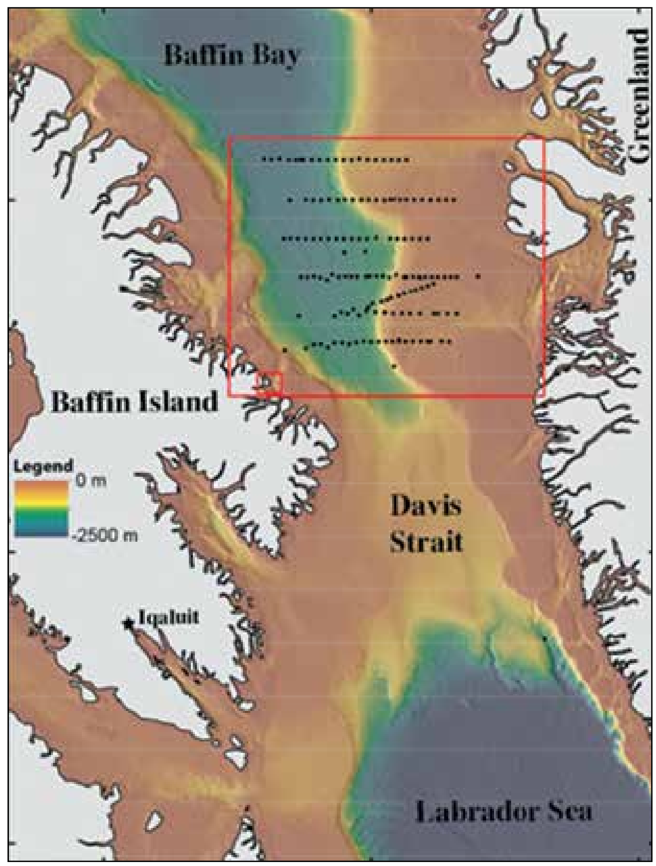


Figure 3. Map illustrating the sampling grid used during the GreenEdge oceanographic cruise on the CCGS Amundsen (red square). Bathymetric data is from the high resolution multibeam echosounder installed aboard the CCGS Amundsen (Gabriel Joyal and Patrick Lajeunesse) and the International Bathymetric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

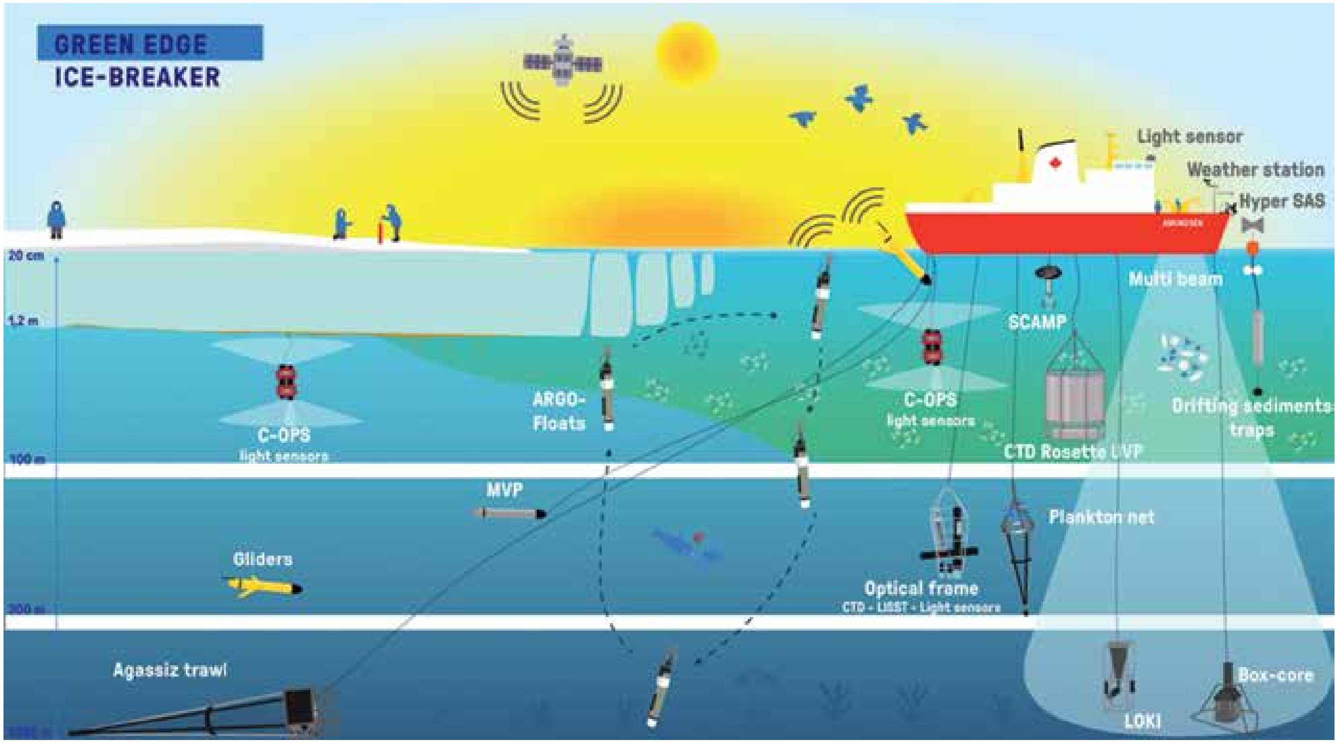


Figure 4. Visual summary of the equipment used during the GreenEdge oceanographic cruise (credit: Julie Sansoulet).

- Bottom mapping
- s-ADCP
- pCO_2 – carbonate system

2017 activities: Deployment of 7 PRO-ICE lagrangian BGC ARGO floats

Claudie Marec (CNRS) and José Lagunas (Université Laval) participated in Leg 2b of the annual ArcticNet campaign (July 13-August 17, 2017) in Baffin Bay (Arctic Ocean), Northwest passage, Queen Maud Gulf and Gulf of Boothia (Figure 5).

During the 2017 cruise, seven BGC (biogeochemical) Argo floats were deployed, following the deployment strategy employed in in 2016 (GreenEdge cruise) where different instruments were used to track the "ice edge spring bloom". PRO-ICE floats are autonomous platforms, equipped with numerous sensors dedicated to characterize the water column. During its life (at least three years depending on the frequency of profiles) a Lagrangian ARGO float drifts, profiling between the surface and the seafloor (or a programmed depth: 1000 m in our case). When at the surface, the

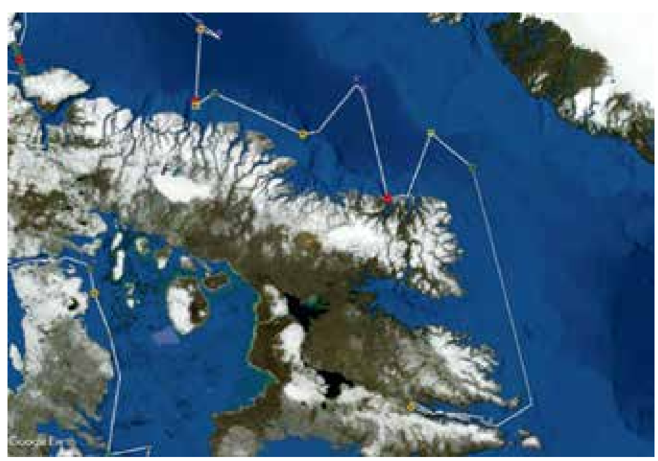


Figure 5. Amundsen's steaming route in Baffin Bay for the Leg 2B, 2017. The deployment sites are named Float 1, 2, 3 and 4.

float is geo-localized and transmits its data using the Iridium communication system.

PRO-ICE floats are equipped with two ice detection systems to ensure a safer navigation in icy waters (avoid surfacing when ice is present). An upward-looking altimeter detects thick ice and icebergs and an algorithm based on sea-water temperature (ISA Ice Sensing Algorithm) is an indicator of the presence of sea-ice.

Each float was equipped with the following sensors: CTD, Radiometer (OCR λ=380, 412, 490 nM, PAR), fluorescence chla, fluorescence CDOM, Backscattering, Suna (nitrates), Optode (Oxygen).

The areas for deployment of the seven floats were selected after a study of the global Baffin Bay circulation. Four theoretical positions were chosen following to those discussions and literature review about the currents in the area (Tang et al, 2003). When available, geo-referenced Radarsat ice maps received daily during the cruise were consulted to ensure that the deployment area in the center of eastern Baffin Bay was ice-free. In addition, composite maps from remote-sensing (AMSR2 for sea-ice concentration and MODIS for chla concentration) were daily generated by Takuvik (Figure 6).

Four BGC Argo floats were deployed on July 20, 2017 in the same area as the floats deployed during the Greenedge cruise in 2016.

takapm006C (WMO 4901804)

- lat: 69°38.136'N/long 60°43.961'W
- bathymetry 1674 m

takapm012B (WMO 4901805)

- lat: 69°38.742'N/long 60°44.949'W
- bathymetry 1674 m

takapm015B (WMO 6902670)

- lat: 69°38.525'N/long 60°43.237'W
- bathymetry 1666 m

takapm008B (WMO 6902669)

- lat: 69°38.948'N /long 60°42.329'W
- bathymetry 1659 m

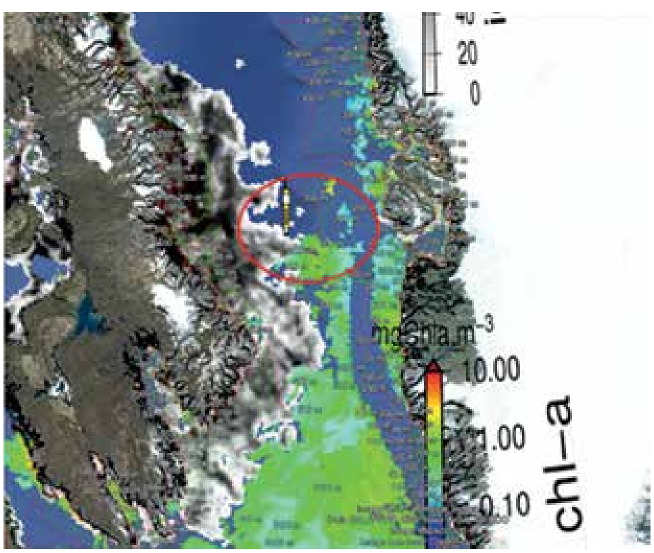


Figure 6. 1st area for four deployments: ice cover (AMSR2) and chl a concentration (MODIS).

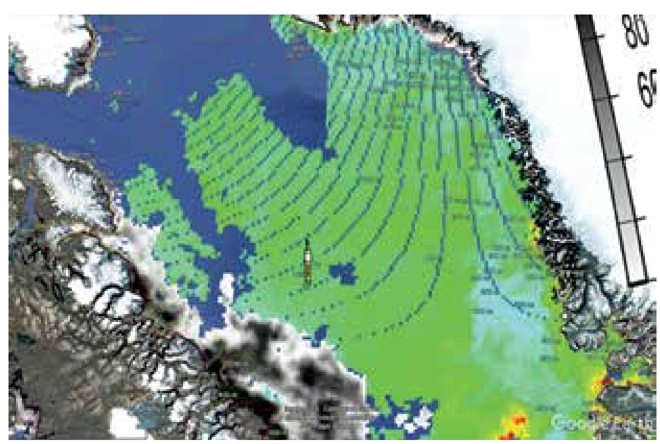


Figure 7. 2nd area for three deployments in Central Baffin Bay: ice cover (AMSR2) and chl a concentration (MODIS).

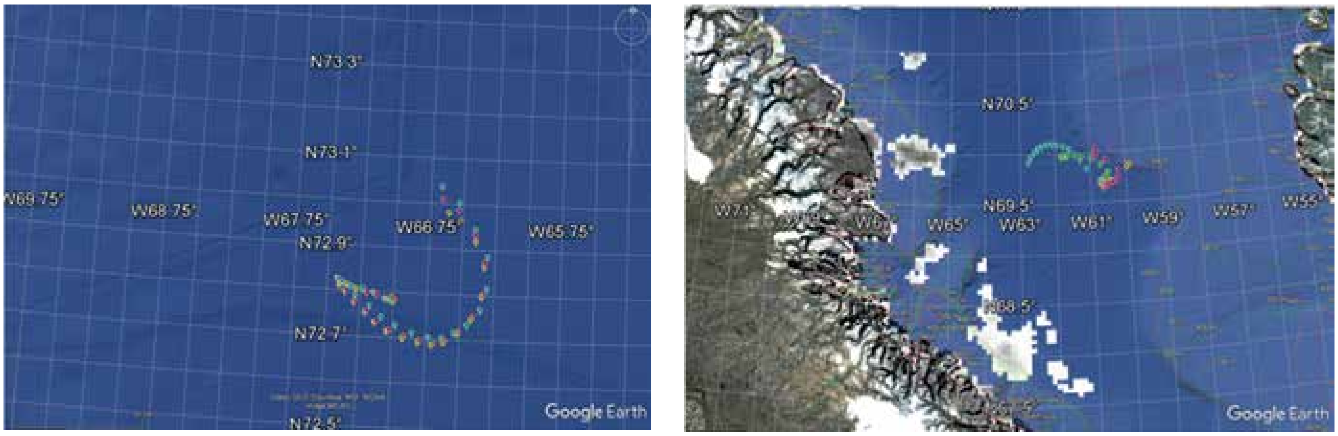


Figure 8. Routes of the 4 & 3 PRO-ICE between deployment and August14, 2017.

An additional three PRO-Ice floats were deployed on July 23, 2017 near the ArcticNet BB2 station), N-NW of deployment area for the floats mentioned above. This site is located at the center of the cyclonic gyre in Baffin Bay and simulations predicted that the floats would continue to navigate in the Central Baffin Bay throughout their lifetime (Figure 7).

takapm007B (WMO 6902666)

- lat: 72°46.295'N/Long 67°01.885'W
- bathymetry 2373 m

takapm016B (WMO 6902671)

- lat: 72°46.127'N / Long 67°00.485'W
- bathymetry 2323 m

takapm017B (WMO 6902829)

- lat: 72°46.180'N/ Long 67°00.400'W
- bathymetry 2372 m

CTD casts were performed at both deployment sites; sampling for HPLC, chl a, Ultrapath (CDOM) and nutrients analyses were performed on the casts for in situ calibrations. Oxygen samples were analysed to check the response of the CTD and to cross-check the optode response of the float.

The floats are programmed on a seasonal pattern and profile the water column daily down to a depth of 1000 m until freeze up. Afterwich, the complete a profile every three days. During winter, the floats park at depth, conduct one profile per month and are unable to surface because of ice-cover. Thanks to a bi-directional Iridium communication system, it is possible to modify float navigation pattern as well as the resolution of the sensors.

Unfortunately, we lost contact with three of the floats before freeze-up but the sampling and navigation functionalities the remaining four floats worked as expected until they parked under the seaice. After ice-melt and retreat in the spring, the floats will be able to surface and transmit the data they collected over the winter (Figure 8).

The frequency of the geolocalised data received from the floats varies accordingly to the month, as described in Table 1. This schedule is dictated by the evolution of ice cover conditions in Baffin Bay and is more intense during the phytoplankton bloom period. This drift and profiling plan accounts for a yearly total of 207 profiles per float.

These profiles provide data from the different sensors measuring the water column between 1000 m and the surface. The resolution of each sensor adjusted to respond differently according to depth, for instance high resolution in the euphotic zone, compared to the layer between 1000 m and 350 m. This is best described

Table 1. Profiling schedule for the deployed ProIce floats, given in number of profiles per month.

Month	No. of Profiles/month	Month	No. of Profiles/month
January	3	July	31
February	3	August	31
March	3	September	30
April	3	October	30
May 1 – May 16	8	November 1-15	15*
May 16 – May 31	15	November 16-30	2*
June	30	December	3

*ice cover dependant

Table 2. Scientific payload sampling rate for the month of September, the last zone is activated whenever a 2000 m bathymetry is available.

	CTD / m	OCR / m	ECO / m	Optode / m	Suna / m
0-10m	0,2	0,2	0,2	1	2
0-50m	0,2	0,2	0,2	1	2
10-350m	1	1	1	1	10
350-1000m	1	-	10	10	30
1000-2000m	10	-		50	50

in Table 2, where the sampling rate of the previously described sensors are modified while ascending through the water column. The last depth zone is activated whenever a 2000 m bathymetry is available.

Data from the floats have been readily available since their deployment. Figures 9, 10 and 11 show an example of preliminary of data sent back by takapm012b (July 26, 2017).

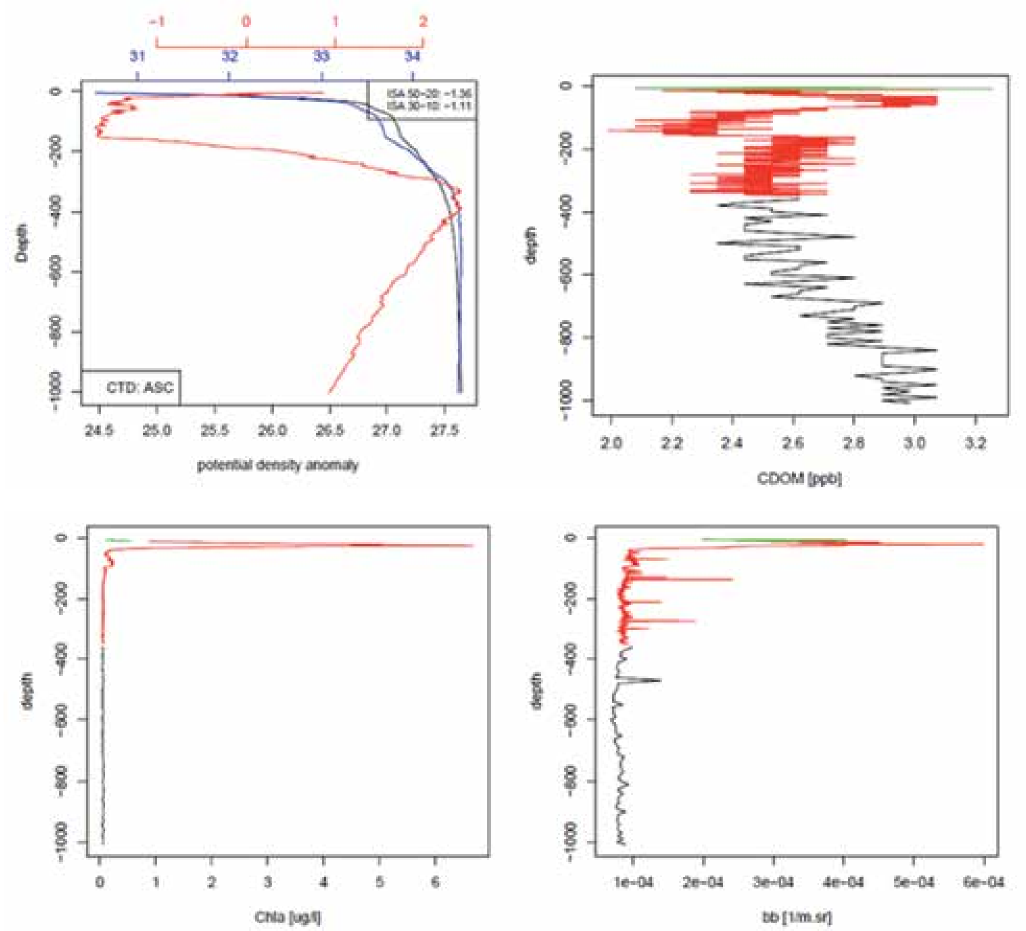


Figure 9. Top left: temperature, salinity and potential density anomaly; top right: CDOM (Colored dissolved organic matter); bottom left: proxy of Chlorophyll-a concentration, bottom right: back-scattering.

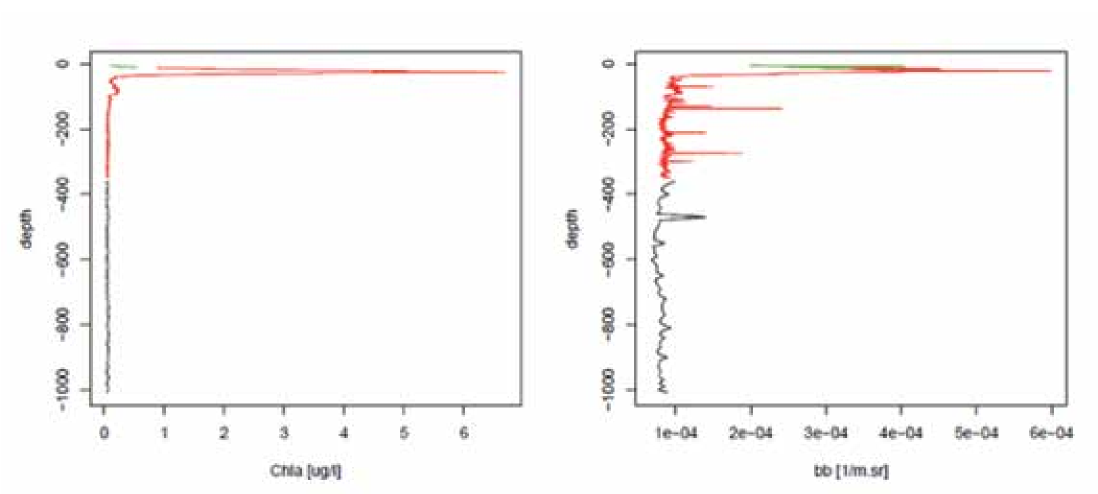


Figure 10. Nitrate (left) and dissolved oxygen data (right) from the BGC floats.

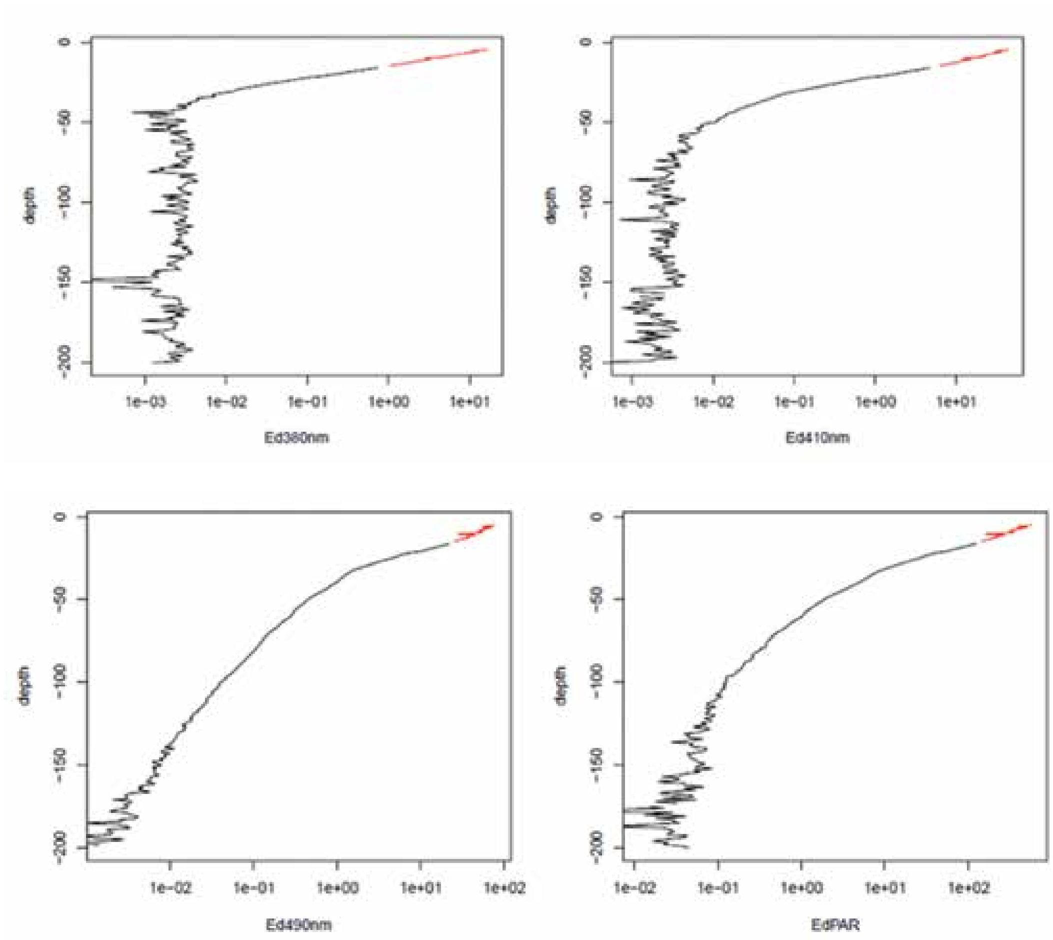


Figure 11. Data from the three radiometers and the PAR sensor (Photo-synthetically Available Radiation).

RESULTS AND DISCUSSION

Work Package 1: Coordination and communication

To date, the GreenEdge consortium has held five meetings. The objective of the first meeting (Ottawa, December 2014) was to plan the field campaign. The four subsequent meetings (Paris, November 2015; Nice, December 2016; Québec City, May 2017 and Paris, February 2018) were dedicated to knowledge transfer, presentation of results, networking and preparation of scientific publications.

Work Package 2: Spring bloom dynamics

During the *Amundsen* cruise, the deep chlorophyll maximum was located between 10 and 14 m. Four major taxonomic groups dominated the plankton community, diatoms, dinoflagellates, flagellates and *Phaeocystis* spp. (Figure 12).

Total abundance ranged from 0.15×106 to 12 ×106 cell L^{-1} with an average abundance of 0.8×106 cell L^{-1} (surface) & 2.8×106 cell L^{-1} (DCM). Globally,

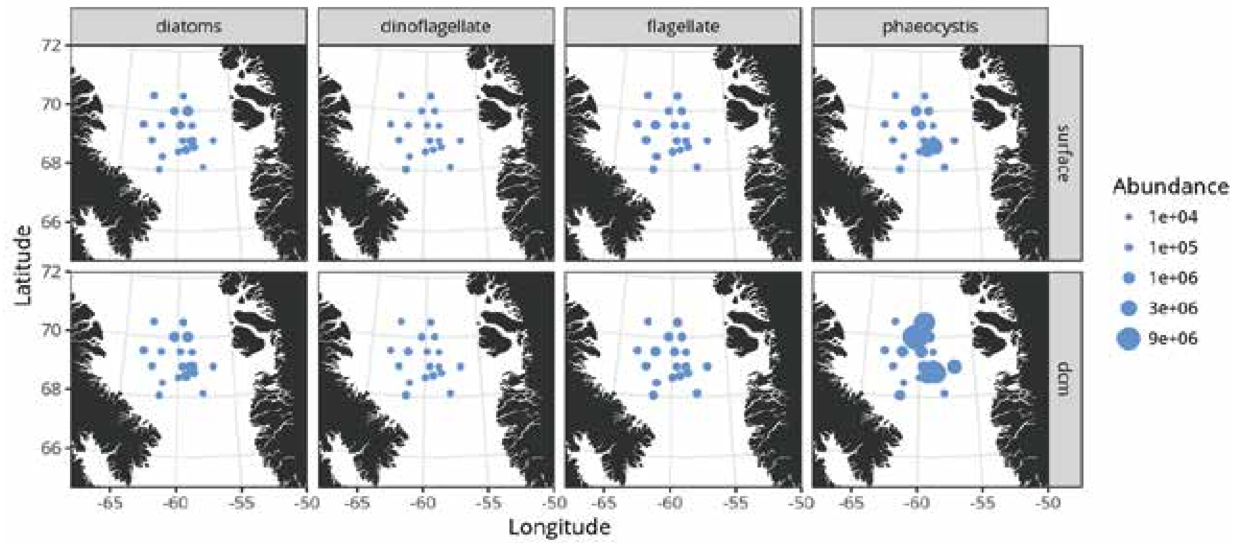


Figure 12. Abundance of taxonomic groups (cells/L) for sampling conducted July 5-11, 2018.

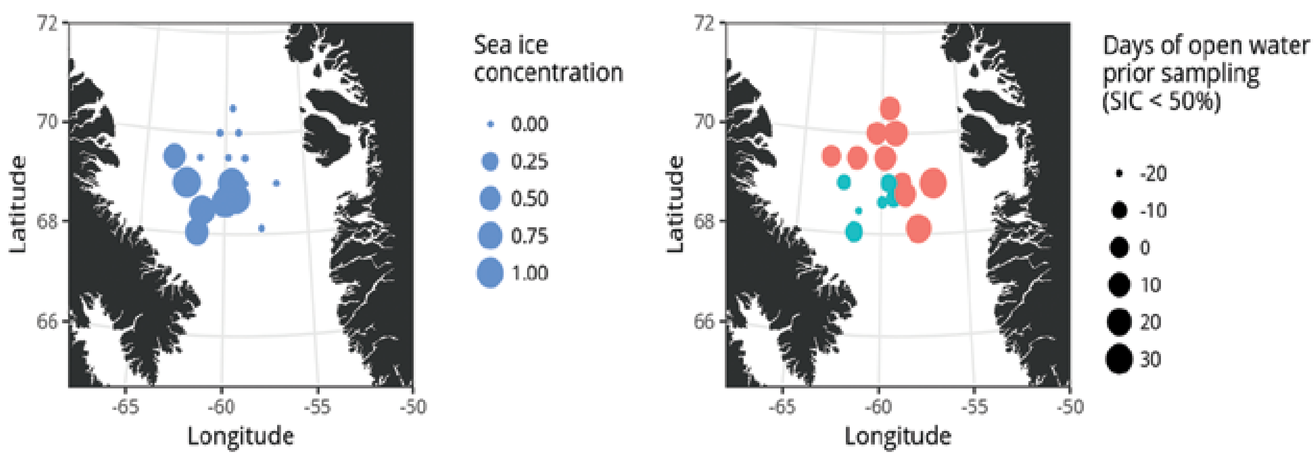


Figure 13. Sea-ice concentration and days of open water (SIC <50%) prior to sampling as derived from passive microwave data AMSR2.

Phaeocystis spp. dominated the community (>50%) coexisting with diatoms such as *Chaetoceros* spp. (maximal concentration 4×105 cell L^{-1}; 12% relative abundance), dinoflagellates (*Gymno*- and *Gyrodinium* spp.), (maximal concentration 2×105 cell L^{-1}; 3% relative abundance) and flagellates (maximal concentration 4.5× 105 cell L^{-1}; 14% relative abundance).

During the sampling period, the eastern stations had been ice free (<10%) for more than 10 days, whereas the western station remained ice covered (>50%) (Figure 13).

There was more light available at the surface than at the DCM. The surface was nitrate depleted in locations where the SIC<50%, which explained the low N:P ratios at eastern stations. Chl a concentrations (range:

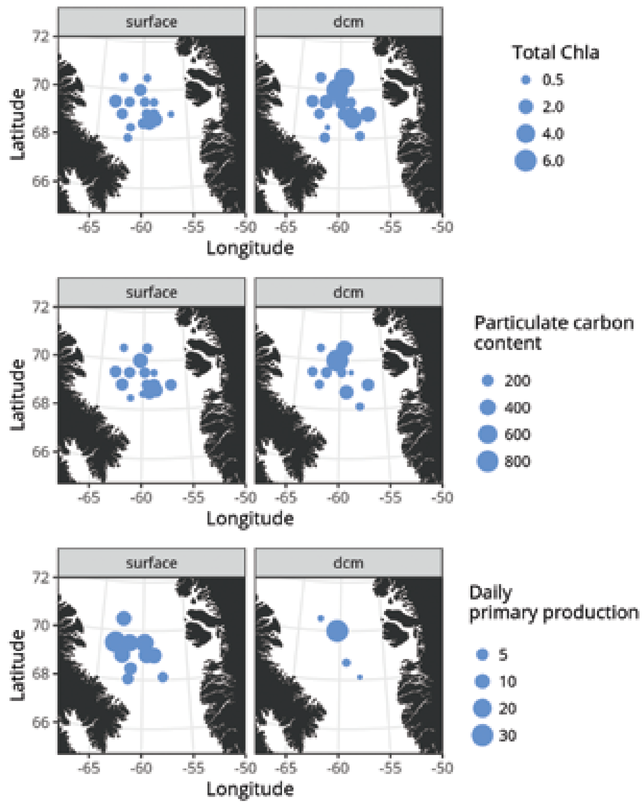


Figure 14. Standing stock Chl a, particulate carbon, and daily primary production rate in µg/L.

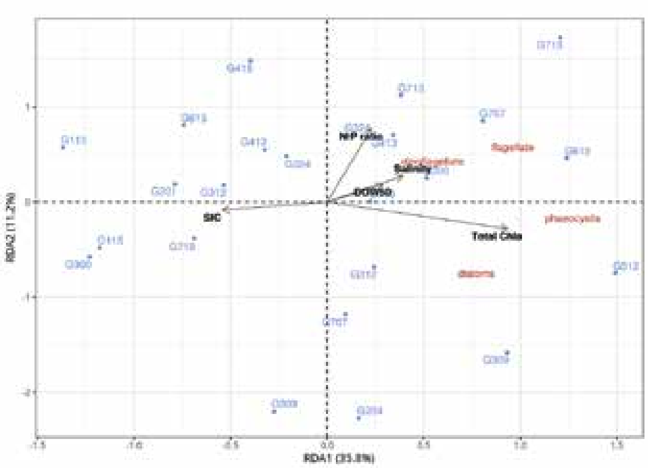


Figure 15. Redundancy analysis.

0.02 to 6.09 µg L^{-1}, with a mean of 0.98 µg L^{-1} at the surface and 2.01 µg L^{-1}at DCM) and particulate carbon content (range: 84 to 867 µg L^{-1}, with a mean of 188 µg L^{-1} at the surface and 243 µg L^{-1}at DCM) followed total phytoplankton abundance. Daily primary productivity was highly variable, ranging from 0.4 to 31.4 µg L^{-1}, with a mean of 12.1 µg L^{-1} at the surface and 8.4 µg L^{-1}at DCM (Figure 14).

Redundancy analysis (RDA) showed that axis 1 explains 35.5% of the variance among explanatory variables. The abundances of all groups increased with Chl a when the water has been ice free for an extended period. Axis 2 is driven by the N:P ratio. *Phaeocystis* and diatoms are associated with low N:P compared to flagellates and dinoflagellates (Figure 15). Multiple linear regressions showed abundance could not be solely explained by any of the individual variables (Figure 16). Blooms enhanced the microbial loop as illustrated by the slightly higher abundances of flagellates and dinoflagellates.

The initiation of the bloom was controlled by light whereas the potential (Arctic water mass) and realized

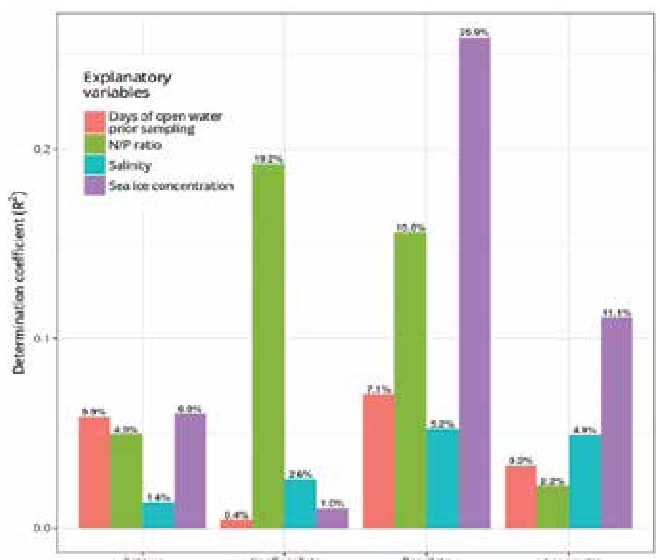
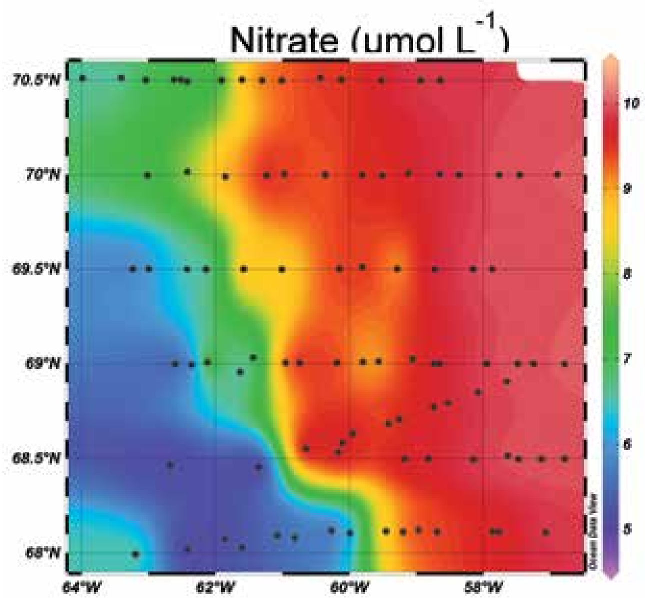


Figure 16. The contribution of individual environmental variables to the total variance explained by each multi-linear model, excluding total Chl a for better visual representation.



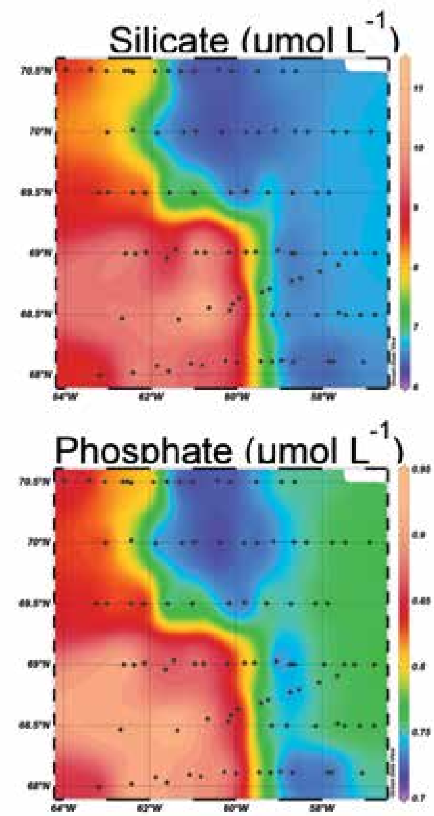
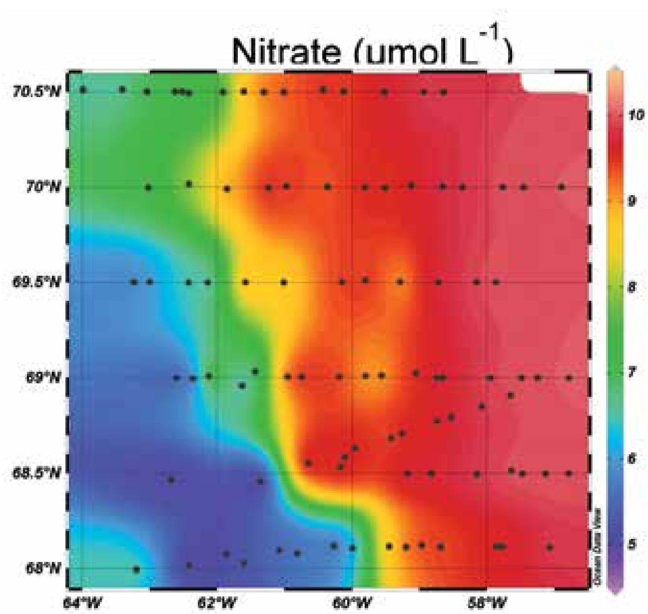


Figure 17. Estimated surface nutrient concentrations prior to the bloom. Expected concentrations of NO_3^- were higher in the Atlantic water (10 - 11 µM) than in the Arctic water (5 - 6 µM), implying that potential PP is higher in the former. The opposite is observed for phosphate and silicate.



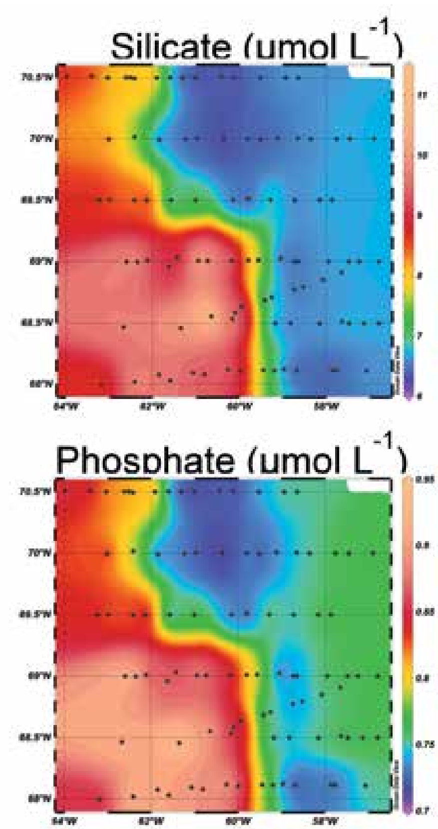


Figure 18. Estimated seasonal drawdown of nutrients.

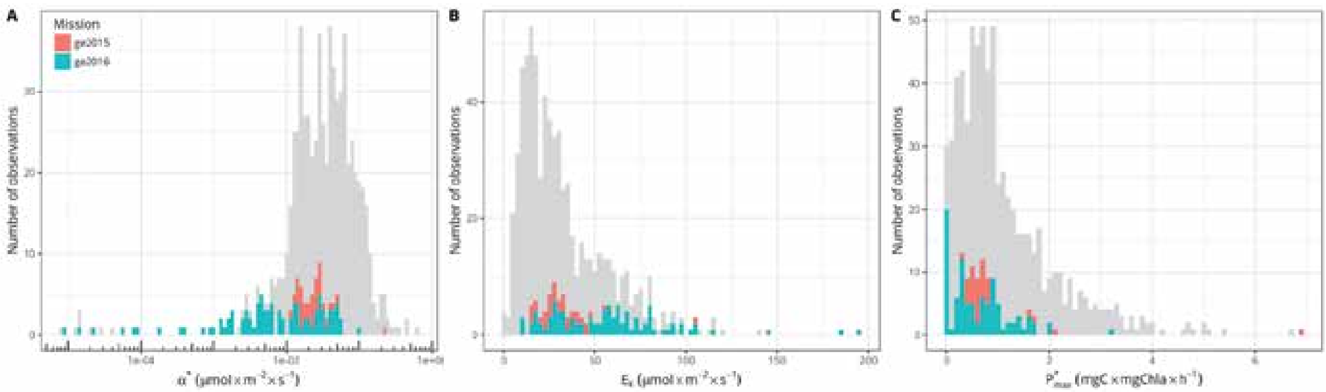


Figure 19. Photosynthetic parameters from the time series at the ice station 2015 (green, n=32), 2016 (pink, n=93) and Arctic data (n=292) from Malina program (Beaufort Sea) and Marine Ecology Laboratory of Bedford Institute of Oceanography cruises (Labrador Sea, Baffin Bay, Foxe Basin).

(Atlantic water mass) net primary production was determined by nutrient availability.

The greater net productivity in the east is partly due to early ice retreat (or lack of winter ice at the easternmost stations) and partly due a greater pre-bloom nutrient reservoir (Figure 17).

A greater fraction of available nutrients was consumed in the east, reflecting the westward progression of the bloom with the receding ice edge. Yet, up to 50% of the estimated pre-bloom inventories were missing in the northwest, suggesting under-ice primary production. Silicate deficits in the east suggest that *Phaeocystis* colonies and diatoms both contributed substantially to the bloom, either simultaneously or in succession. At the time of sampling, the cumulative water-column drawdown of nutrients was much greater in the east, reflecting both the larger pre-bloom inventories and earlier ice retreat there (Figure 18).

Production vs irradiance (P/I) curve parameters were calculated at the ice camp both in 2015 and 2016. The low E_k medians (22-28 mol m^{-2} s^{-1}) for Arctic waters suggest a low light acclimation of the phytoplankton community (Figure 19B). The higher E_k median from coastal Baffin Bay 2016 (55 mol m^{-2} s^{-1}) may reflect the PSB captured during the field season when higher light levels were observed. The wide range in E_k suggests powerful acclimation capacity of Arctic

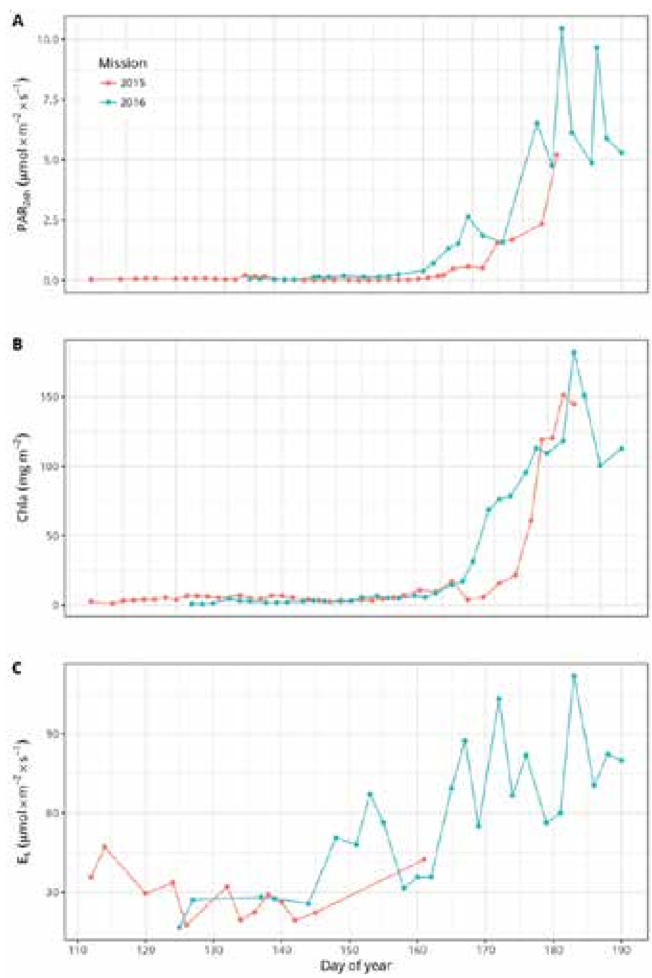


Figure 20. Ice camp time series data for A) PAR , B) Chl a and C) E_k.

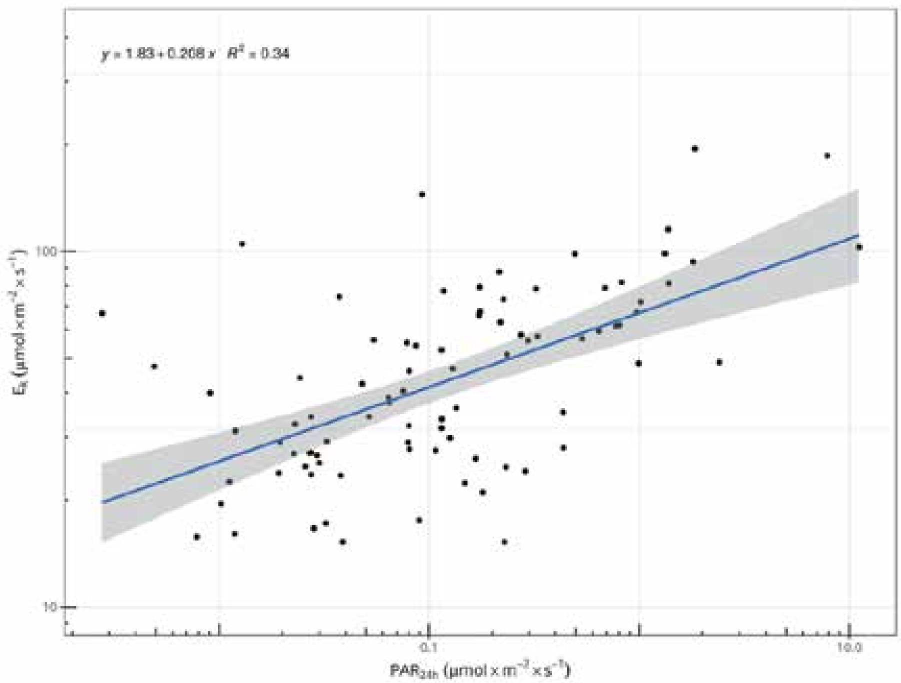


Figure 21. Assimilation light intensity (E_k) in the water column at the ice camp as a function of PAR.

phytoplankton to maintain productive capacity under a wide range of light conditions. Sampling began and finished earlier in 2015. By continuing later in the season in 2016, we hope to catch more of the bloom. Data from the two years is similar for the overlapping period (Figure 20). Beginning in mid-June (DOY >160), more light is able to penetrate beneath the ice enhancing phytoplankton growth and the accumulation of biomass. E_k shows a strong positive relationship with PAR (Figure 21), supporting the strong acclimation capacity of Arctic phytoplankton species and the importance of considering light-related seasonal variability in models. The range in the photosynthetic efficiency at low light (* - Figure 19A) was broader and lower in 2016 (0.006 mol m^{-2} s^{-1}) than in 2015 (0.022 mol m^{-2} s^{-1}), probably due to acclimation to higher light levels observed in 2016.

Work Package 3: Related carbon transfer through the food web and towards the bottom sediments

Zooplankton samples were collected using integrated vertical net tows (200 µm mesh) during the GreenEdge cruise aboard the CCGS *Amundsen*. Identification and count were made to the lowest taxonomic level. The spatial-temporal variability of plankton and particle size was recorded using a UVP5 both at the ice camp and during the cruise. The abundance and distribution of both in-situ particles (>150 µm) and plankton (>500 µm) were documented. The dynamic of fish and their prey were sampled using a Tucker net (0-90m), IKMT (targeted depths), Beam trawl (seafloor) and Simrad EK60 echo sounder.

Mercury toxicity, general health and foraging ecology of several species of seabirds was investigated by destructive sampling by a team from Aarhus University (Denmark). During the *Amundsen* cruise, seabirds were shot and collected. Their stomach

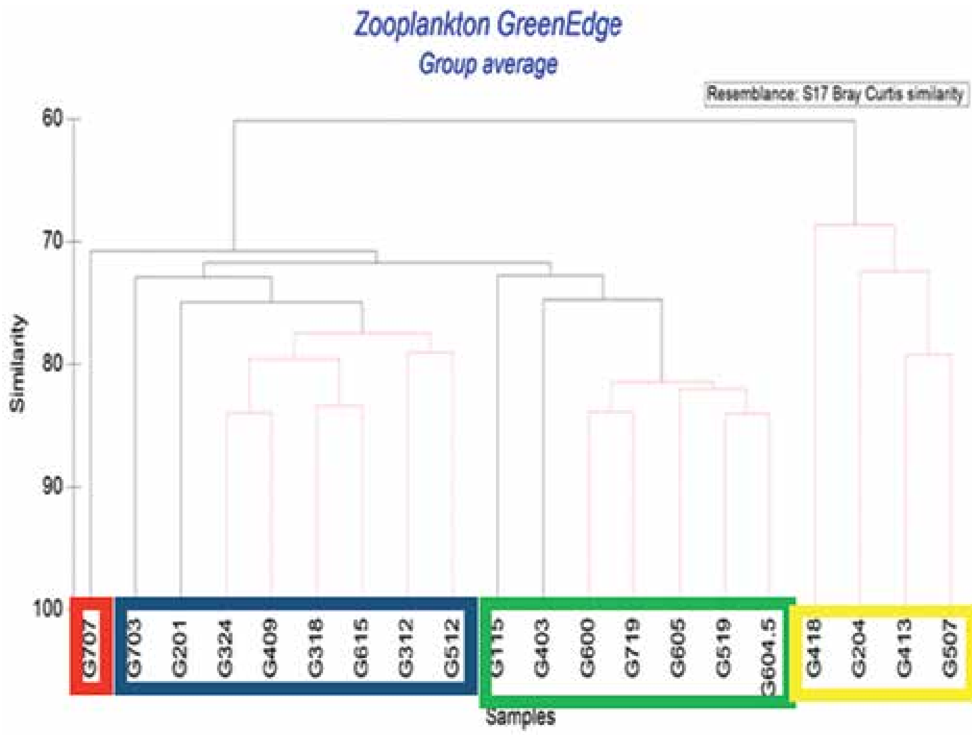


Figure 22. Zooplankton distribution during GreenEdge cruise.

contents were examined and tissue samples were analysed for major contaminants. Blood clinical-chemical parameters assays were also performed. The importance of sea ice for ice-associated thick billed mures (*Uria lomvia*) was evaluated by an analysis of highly branched isoprenoid (HBI) lipid content in their tissues. Diene is a proxy for ice, whereas Triene is an open water biomarker.

Sediment traps were deployed at 25 m and 100 m depths during the ice camp and *Amundsen* cruise to monitor the intensity and composition of particulate matter exported under the ice.

Stable isotope analysis (SIA), fatty acid (FATMs) and IP25 biomarkers were used to characterize the benthic trophic structure and carbon transfer pathways, diets of bottom organisms and origin and availability of nutrients in the seabed.

Bivalves (*Mya truncata*) were collected near Qikitarjuaq and in Young Sound (Greenland) to trace pelagos benthos coupling and reconstruct

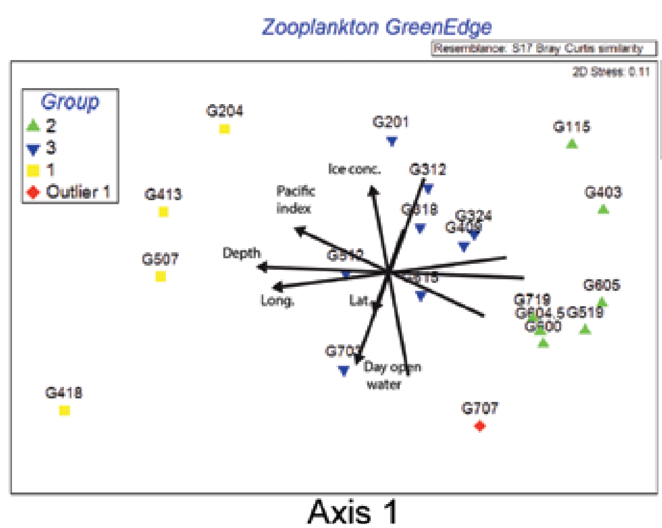


Figure 23. Partition of zooplankton groups during Greenedge cruise .

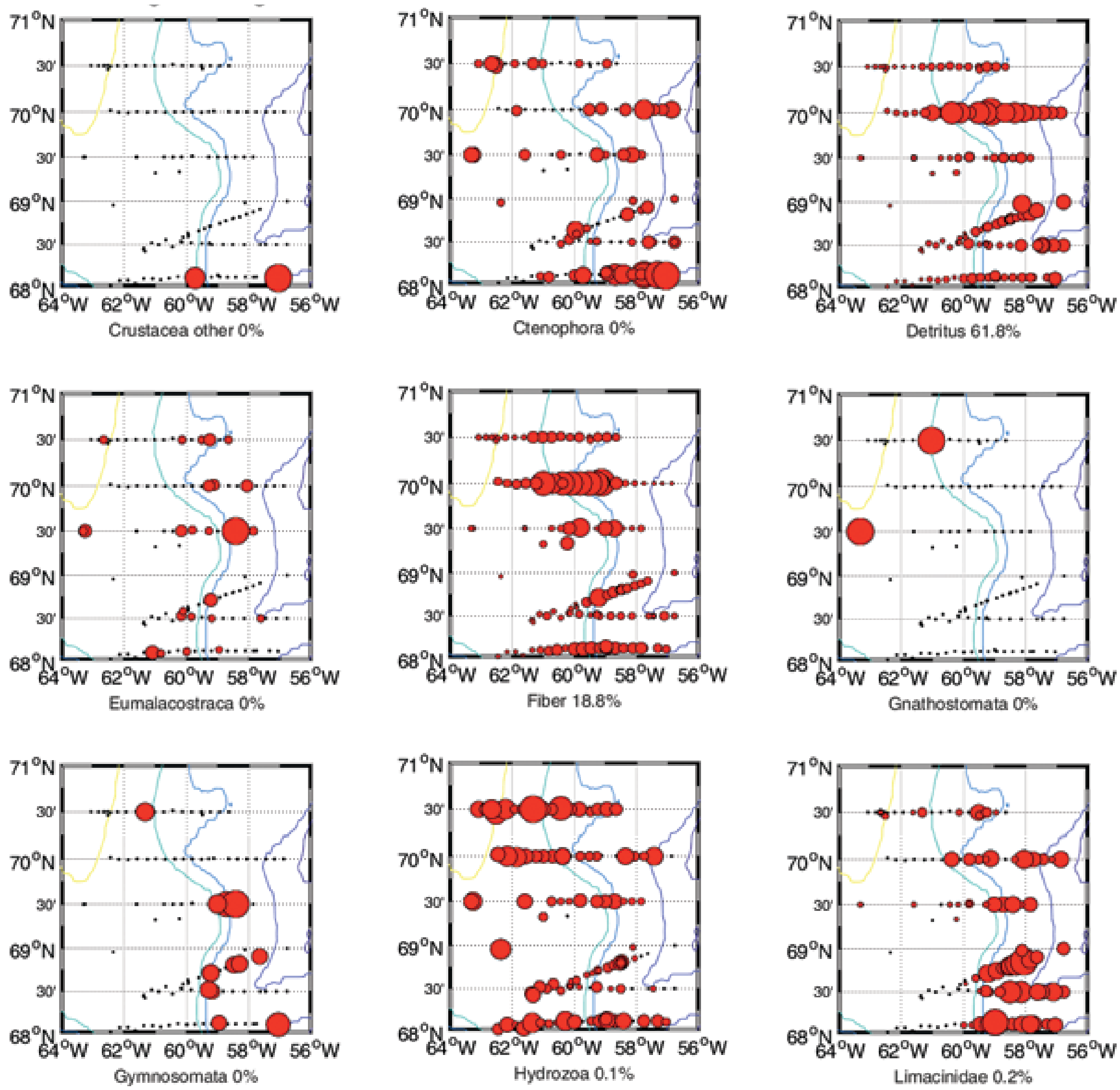


Figure 24. Relative abundance of Limacindae away from the ice edge.

environmental conditions from growth patterns and shell geochemistry.

To understand how changes in environmental conditions affect benthic biogeochemical cycling during the spring, sedimentary organic matter (pigments, C, N, diatoms) were characterized and incubated for measurement of biogeochemical fluxes (O_2, nitrate, ammonia, phosphate, silicate). A comparison was also made with other regions.

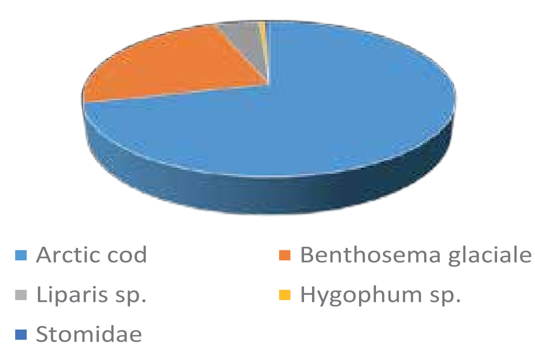


Figure 25. Distribution of fish species during the GreenEdge cruise (n=191).

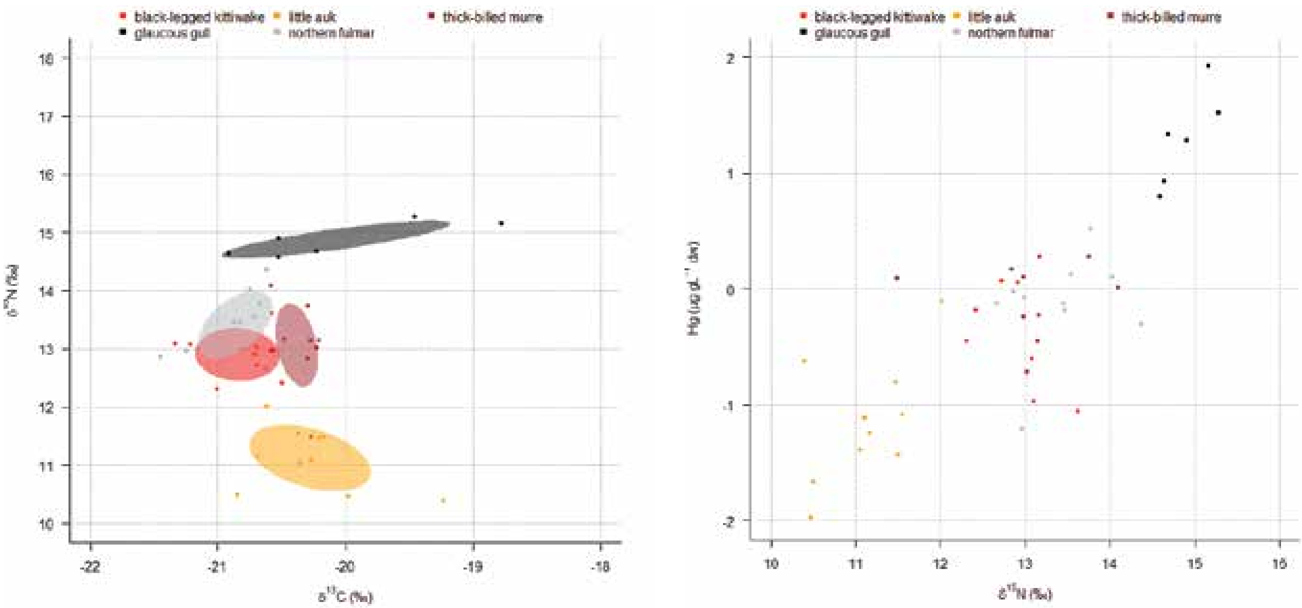


Figure 26. Ecotoxicology of Seabirds collected during the Green Edge cruise.

The main objective of this working group was to track the fate of the phytoplankton spring bloom in the marine ecosystem. The first aspect was to look at zooplankton distribution through net tows and UVP. Cluster analysis identified three main faunistic groups (Figure 22).

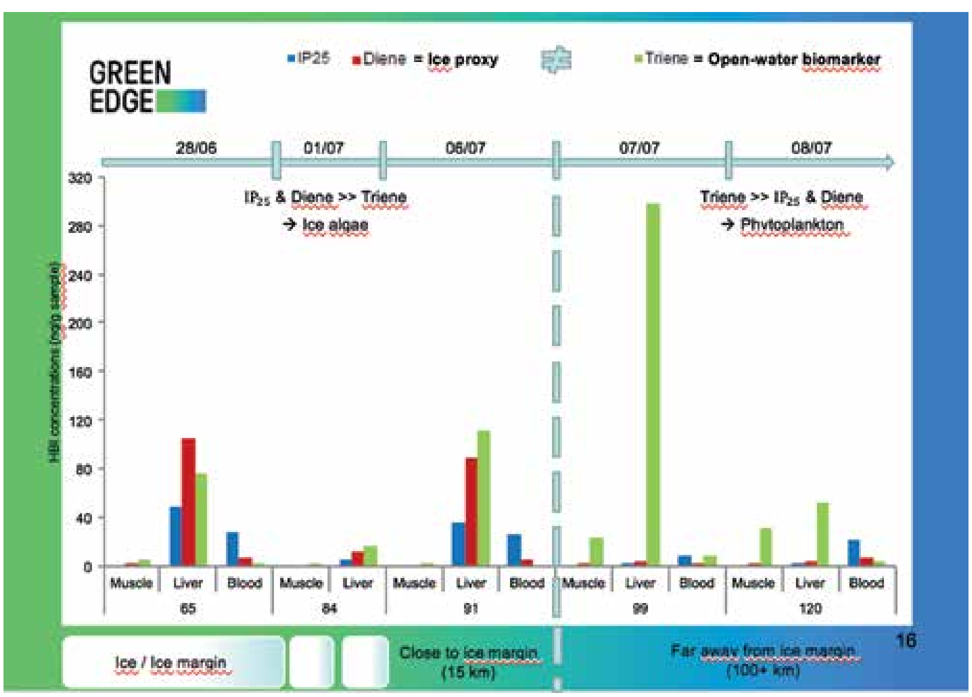


Figure 27. Highly branched isoprenoid (HBI) lipids in the tissue of thick billed mures a function of feeding distance from the ice edge.

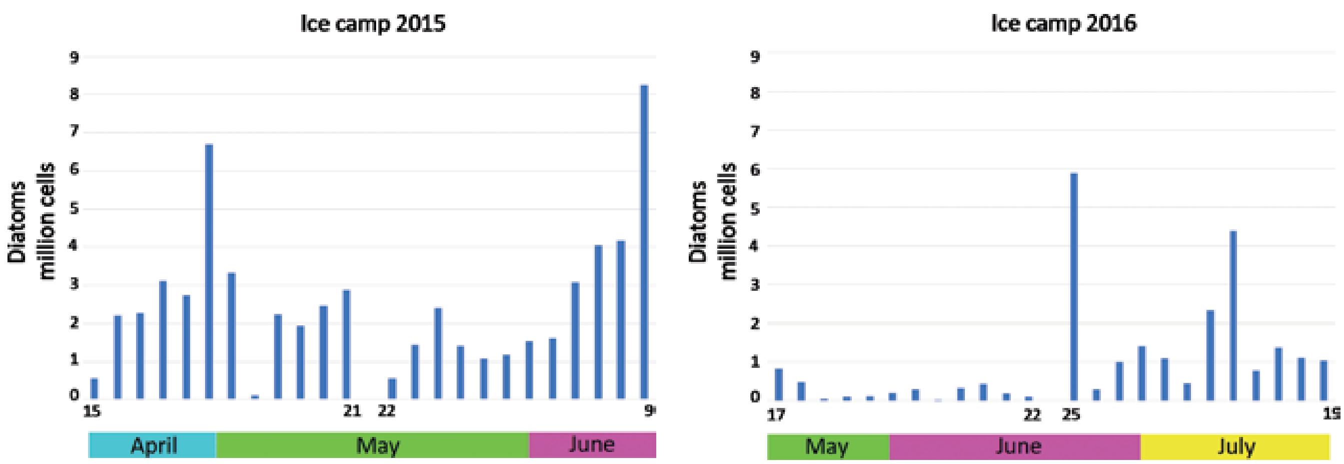


Figure 28. Quantity of diatoms as a function of date during the 2015 and 2016 ice camps.

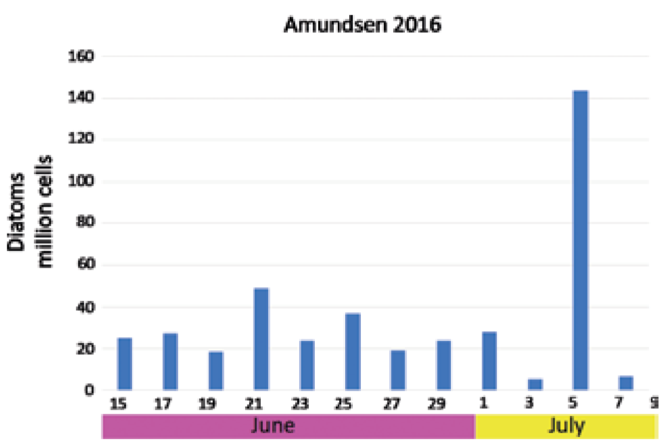


Figure 29. Quantity of diatoms as a function of date during the Amundsen cruise.

Group partition is supported by Non-Metric multiDimensional Scaling analysis (NMDS), with groups separating mainly along first axis (Figure 23). Multiple regressions, using the scores of NMDS and environmental variables, showed that variability in species assemblages was mainly driven by station depth, East-West longitudinal gradient and the relative pacific water contribution. Three assemblages were found and related to an east-west gradient. UVP showed that the zooplankton was mainly composed of copepod with additional species in open water condition (i.e. *Limacindae*, Figure 24). Fish sampling showed a dominance of Arctic cod, with a smaller proportion of glacier lantern fish (*Benthosema glaciale*) and minor components of other species (Figure 25).

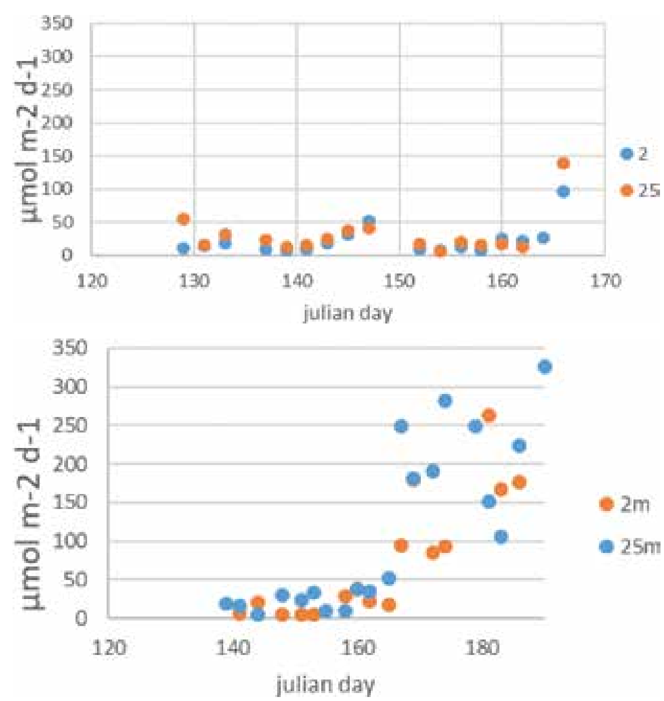


Figure 30. Fluxes of biogenic silica at the 2015 and 2016 GreenEdge ice camps at 2 m and 25 m depth.

Clinical healthy birds with similar biogeochemistry and ecotoxicology compared to conspecifics in northern Baffin Bay, although temporal change seemed to occur (Figure 26). Mercury contents were high in some birds. Measurements on seabird diet showed a variability in IP25 signature, indicating that birds near the ice edge fed more on ice algae whereas, in open waters, the signature was more related to phytoplankton (Figure 27).

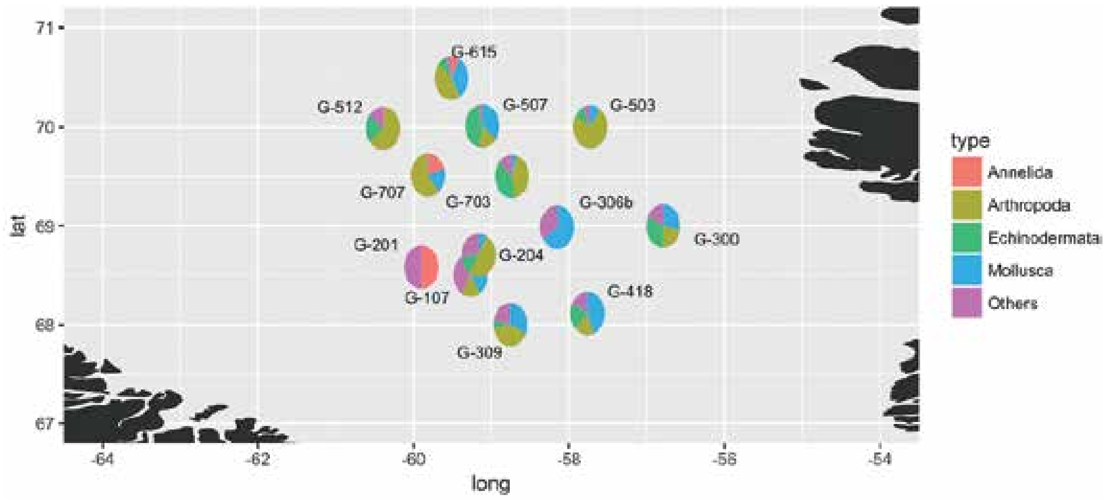


Figure 31. Distribution of benthic assemblages across in Baffin Bay.

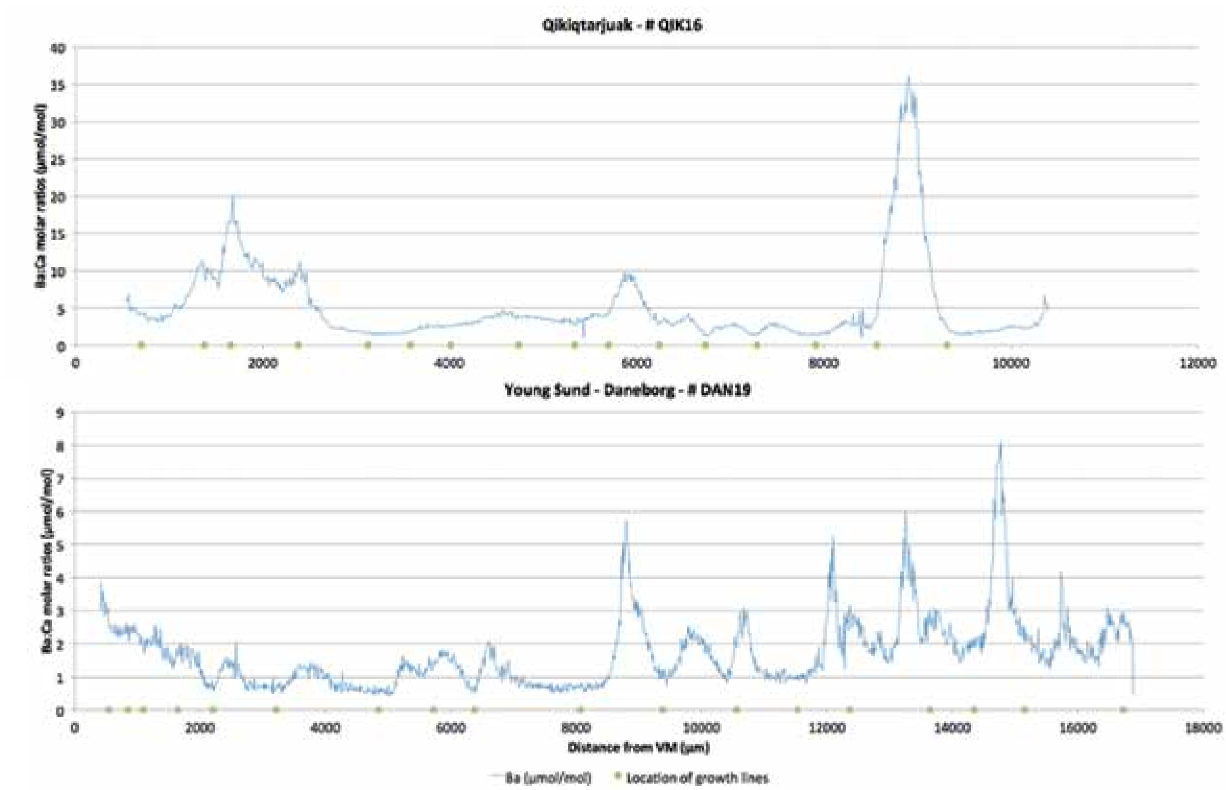


Figure 32. Ba:Ca molar ratio in mussel shells as a function of time before present. Note that levels are higher in Qikiqtarjuaq (top), indicating a higher, more irregular export of diatoms to the benthos at the Qikiqtajuaq site and that the Greenland samples have only one annual peak.

Diatom fluxes were 10 to 25 times higher during the *Amundsen* cruise than at the Ice camp in 2016. This may have been due to nutrient availability or the effect of tide (Figure 28 and 29).Biogeochemical cycling under spring conditions showed strong regional differences in sedimentary organic matter quality, but no regional difference in the benthic response.

Dissolution and sinking of biogenic silica were low (1-5% of production) during the 2015 ice camp,

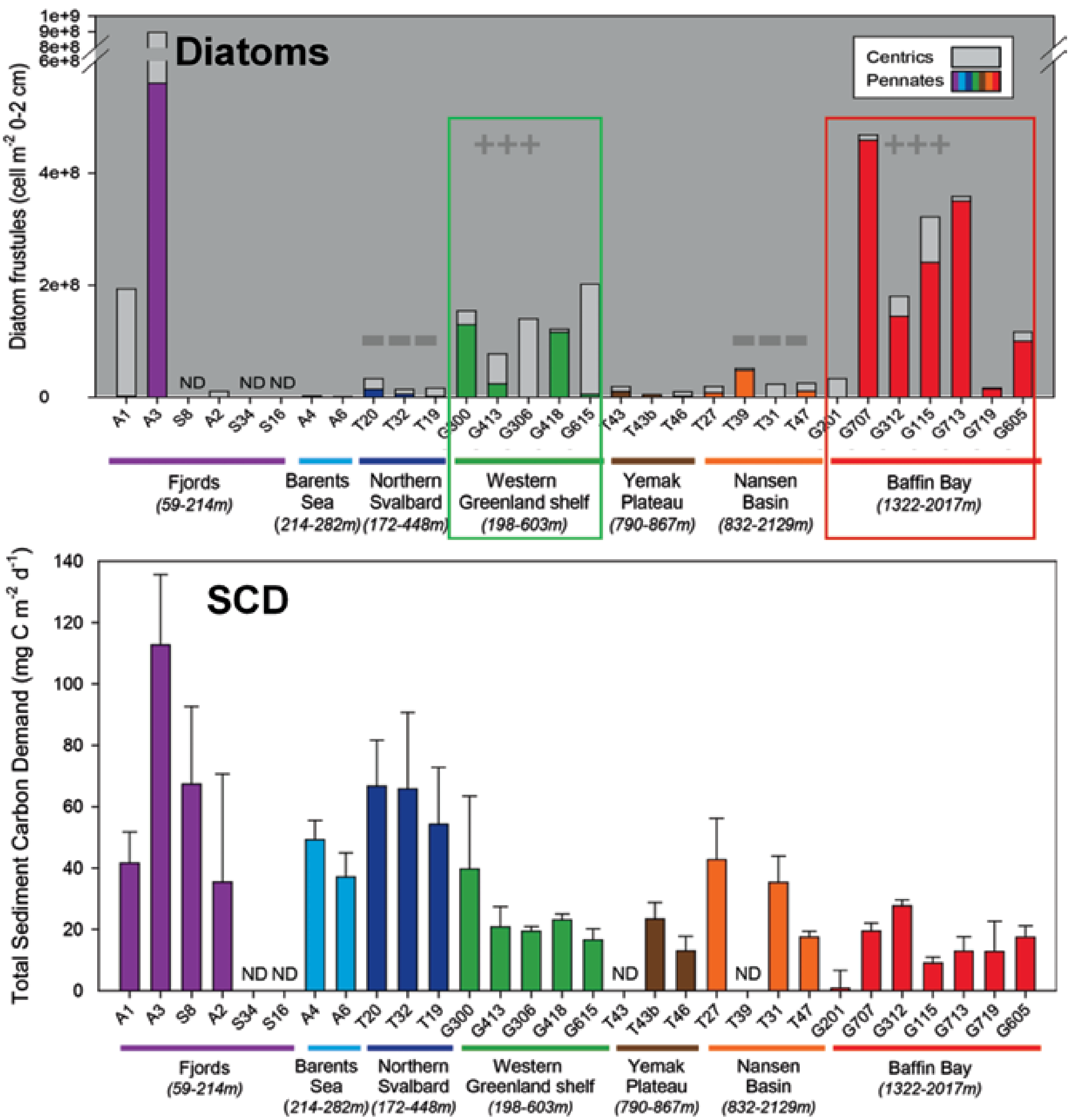


Figure 33. Regional differences in benthic function across the Arctic.

leading to an accumulation of bSI in and directly under the ice. At the 2016 ice camp, biSI accumulated in the ice until mid-June, after which it moved into the water column (Figure 30).

Studies of benthic composition in the area revealed variabilities in the benthic assemblages (Figure 31). Arthopoda (38.3%) was the most abundant phylum, followed by Mollusca (25.8%), Echinodermata (20.2%), and Annelida (5.1%). Porifera, Cnidaria, Chordata, Bryozoa, Nemertea and Brachiopoda together accounted for 10.6% of the benthic fauna.

The sclerochronology study showed variability between the mussels from Qikiqtarjuaq where shells grew faster than the mussels from Greenland site. The Ba:Ca ratio in shells from Qikiqtarjuaq indicated an higher

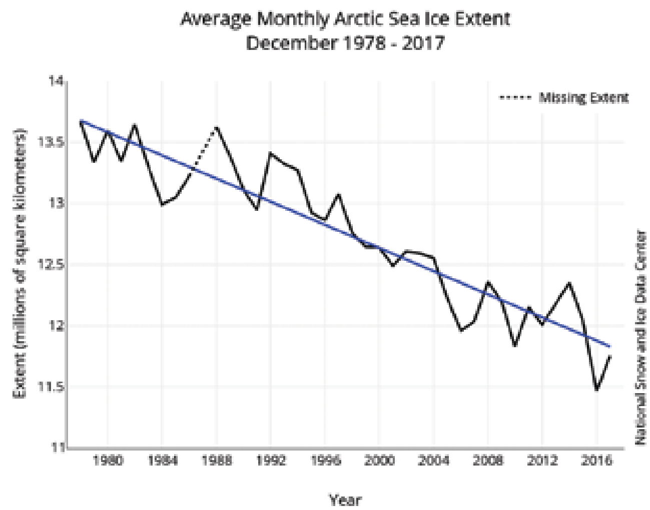


Figure 34. Arctic sea ice extent 1978-2017.

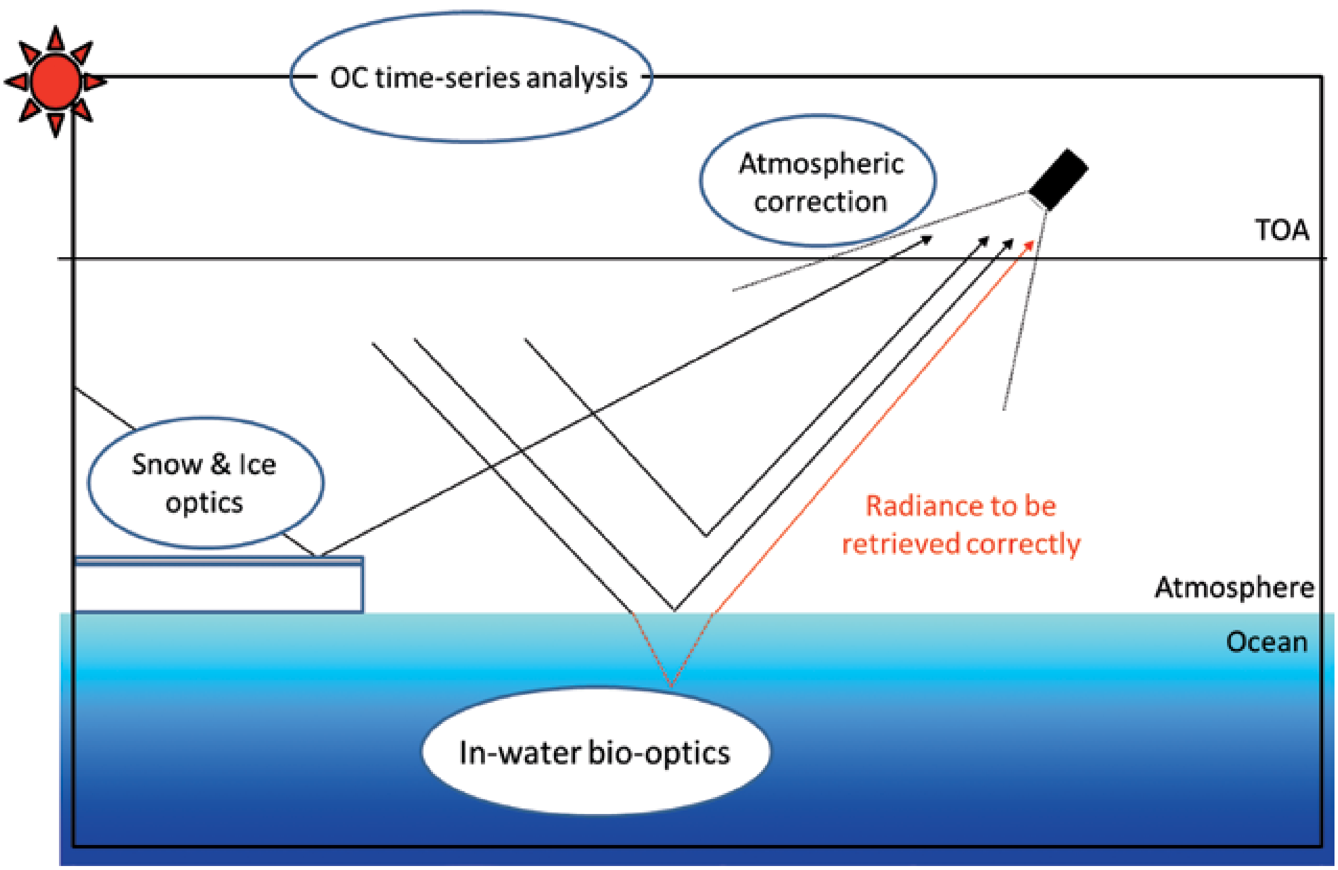


Figure 35. Overview of the four components of WP4 that can be investigated through remote sensing of ocean colour.

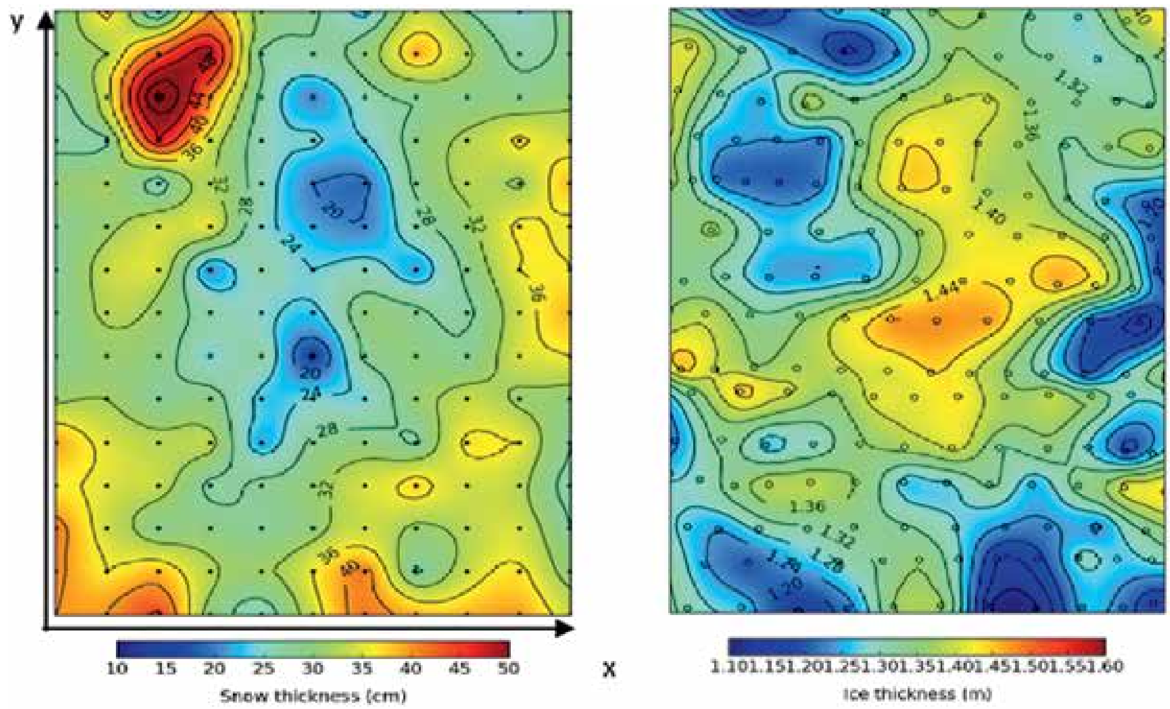


Figure 36. Snow and ice thickness over the same study area.

sedimentation in western Baffin Bay compared to the Greenland site (Figure 32).

Preliminary results of benthic function showed strong regional differences in sedimentary organic matter quality. Despite low vertical fluxes, GreenEdge stations had higher pigments and diatoms contents than other sites across the Arctic (Figure 33). No regional difference was found in the benthic response. Surprisingly, temperature and depths are not the most important factors for the recycling of C, N, P and Si. However, individual nutrients are impacted differently by environmental factors.

Workpackage 4: Remote Sensing

It is globally accepted that sea ice in the Arctic Ocean has decreased in terms of both its extent and thickness (Figure 34). This change allows the light to penetrate into the water column. The seasonal ice zone is more common than in the past. It is expected that this physical change in addition nutrient dynamics and timing of sea ice retreat influences phytoplankton phenology and primary production.

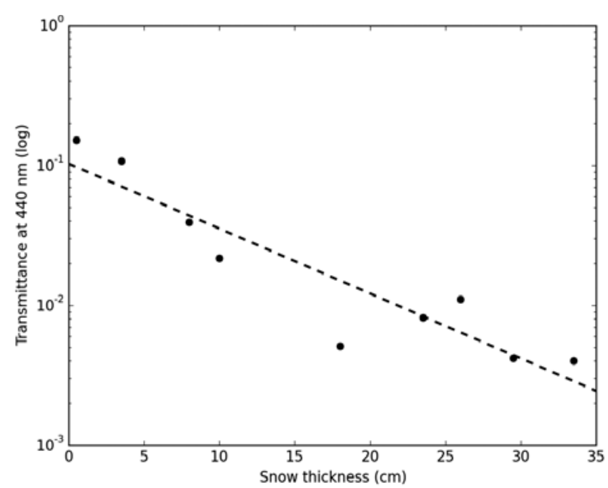


Figure 37. Light transmittance (440 nm) through sea ice as a function of snow thickness.

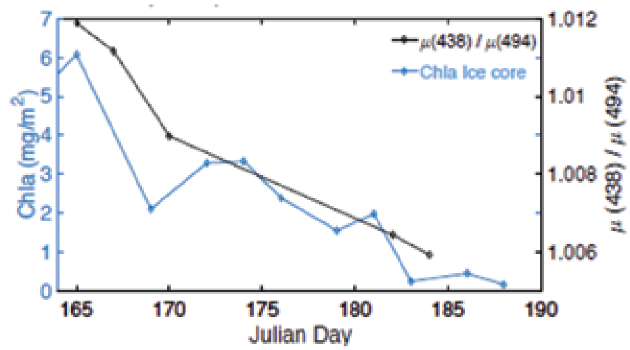


Figure 38. The relationship between chl a at the bottom of the ice sample and ratio of mu at 438 and 494 nm as a function of Julian day.

The four specific objectives of WP4 are atmospheric correction, snow and ice optics, in-water bio-optics, and an ocean colour time series (Figure 35).

Monitoring snow-ice system: observations and simulations

When using ocean colour data for icy waters, there is a contamination issue due to sea ice: adjacency effect and subpixel contamination. To solve this issue, it is necessary to gain a better understanding of snow and ice optics as well as in-water optical properties. Knowledge of snow and ice optics is important to comprehend the signature related to adjacency effect and subpixel contamination. This knowledge is also useful to estimate underwater light field beneath the ice as an input of surface information including albedo, snow and ice type. In-water optical properties are directly linked to water leaving radiance that can be retrieved using ocean color data after an appropriate atmospheric correction is applied. In-water optical properties are essential to develop in-water algorithms.

There was a large heterogeneity of snow thickness relative to ice thickness over the study area. For example. Snow thickness varied about a factor of 2.5 (from 20 to 50 cm), while ice thickness varied 15 % (from 1.2 to 1.4) (Figure 36). In this condition, transmittance of light at a wavelength (440 nm, for example) is well correlated with snow thickness and transmittance can be estimated as a function of snow thickness (Figure 37).

As ice thickness decreases, mean cosine of downwelling radiance (μ) decreases as light begins to penetrate the water column. A good correlation was found between chlorophyll a at the bottom and μ (Figure 38), indicating that concentration of ice algae can be modeled using ratio of average cosine.

Normalized radiance beneath the ice can be modelled using 3D radiative transfer model based on monte-carlo method as a function of solar zenith angle for different surface types, as shown for wet and dry snow and melt pond in Figure 39. This result basically suggests that light field beneath the ice can be modeled as an input of surface information. This modelling approach is very useful for primary production estimate beneath the ice.

A study of in-water optics illustrated a good correlation between chl a concentration of the bottom of the ice and phytoplankton absorption. However, a clear decrease in these variables was observed after the day 175. This decrease corresponded well with increases

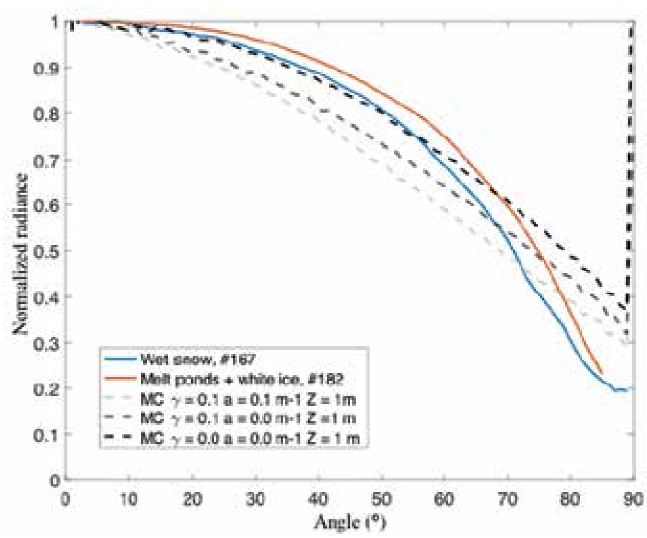


Figure 39. Normalized radiance beneath the ice as a function of solar angle for wet snow, dry snow and melt ponds at the Green Edge ice camp (Lambert-Girard et al. in prep).

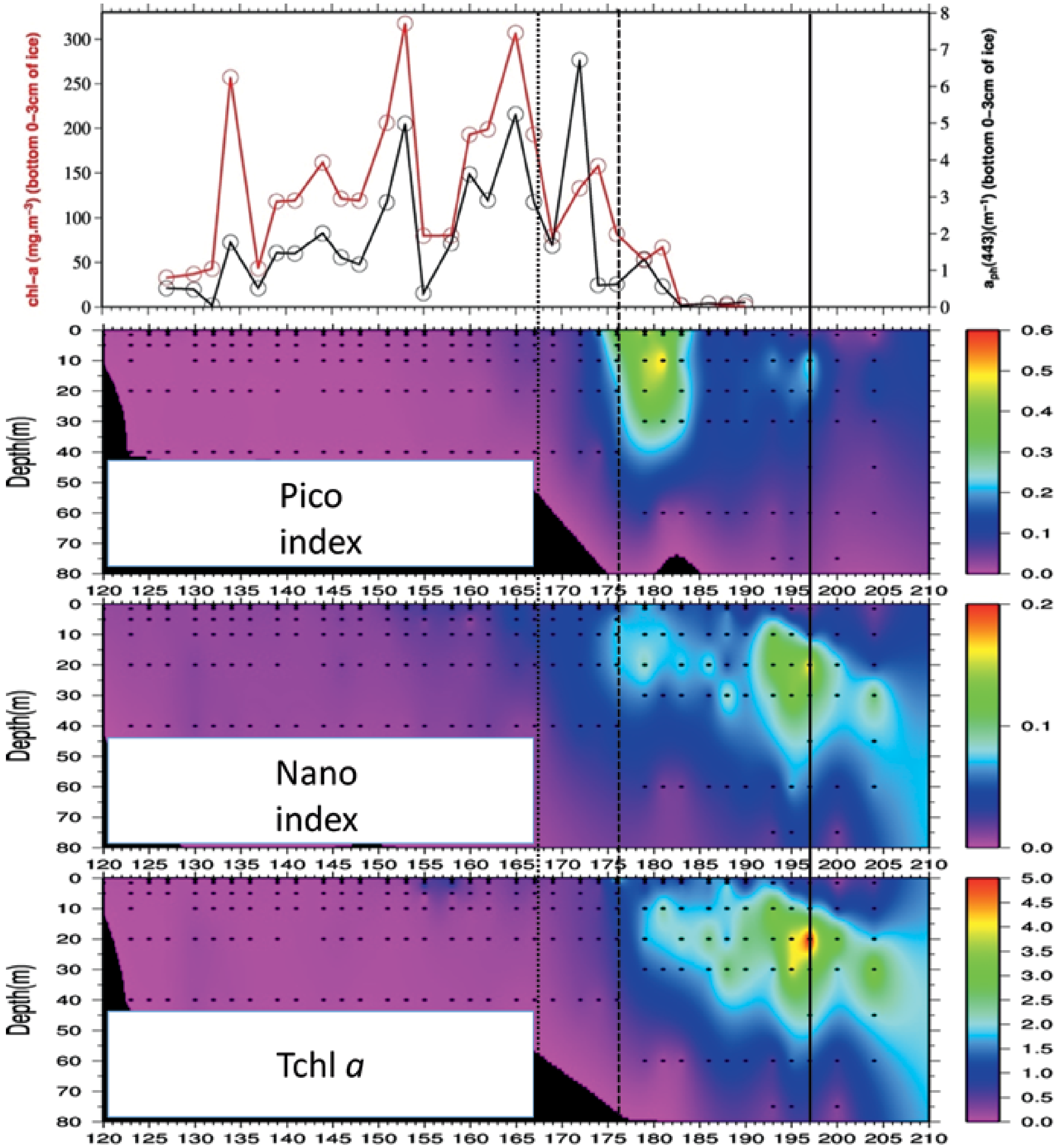


Figure 40. Relationship between chl a concentration of the bottom of the ice, phytoplankton absorption and evolution of phytoplankton size classes over the bloom period.

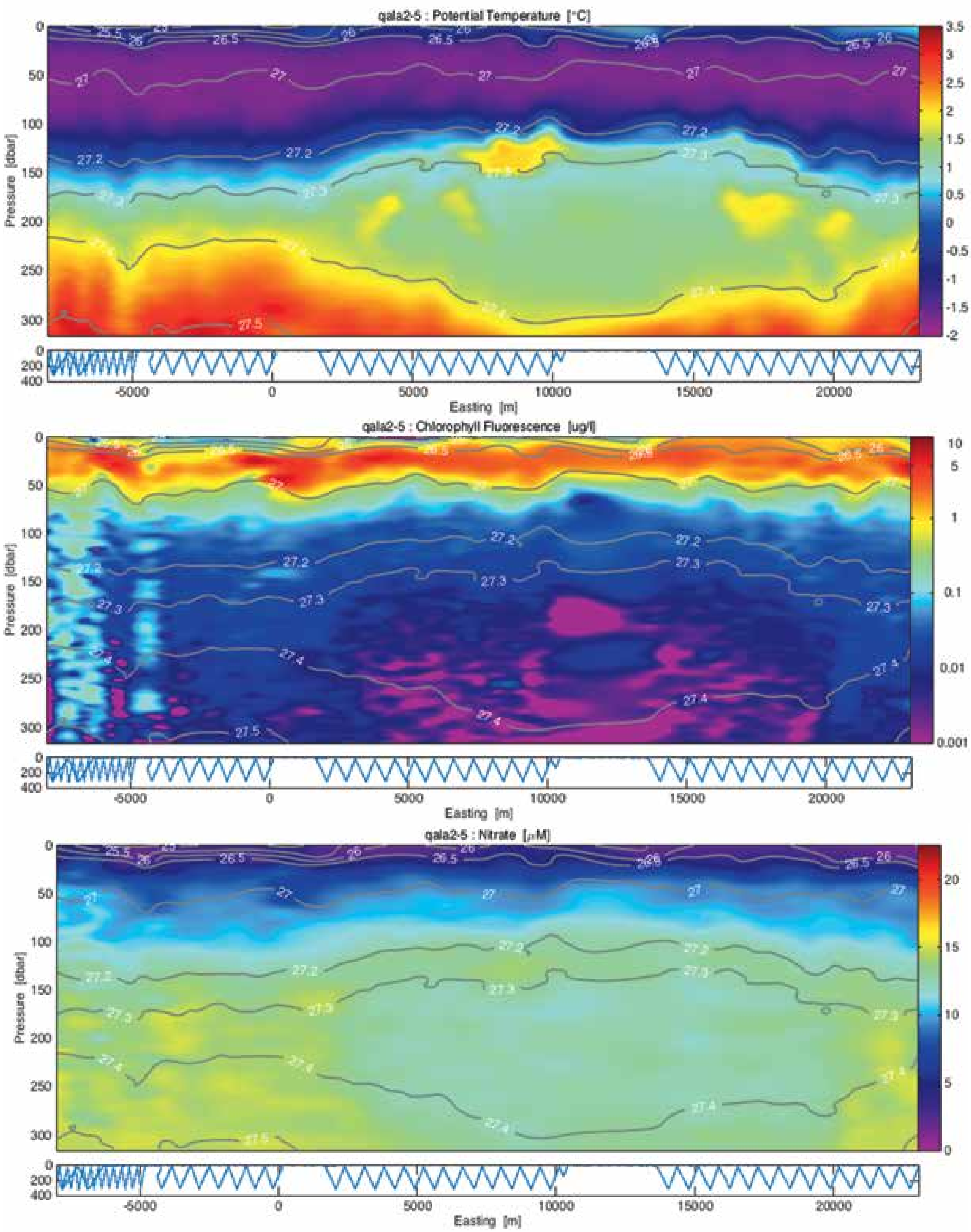


Figure 41. Temperature, chlorophyll fluorescence and nitrate concentration along a glider transect during the GreenEdge oceanographic cruise.

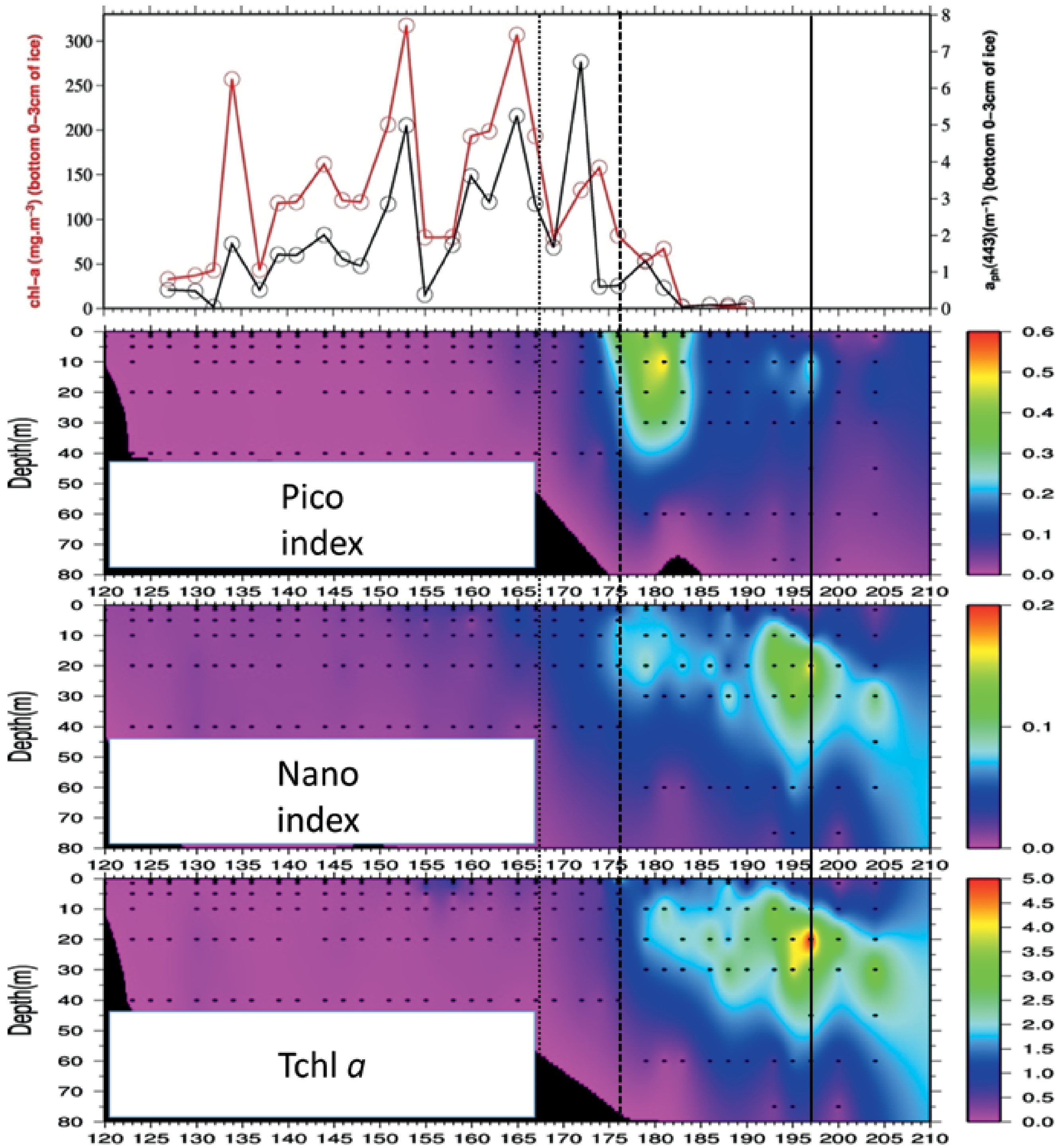


Figure 42. Temperature, chlorophyll and nitrate concentration as a function of depth and time from Bio-Argo data.

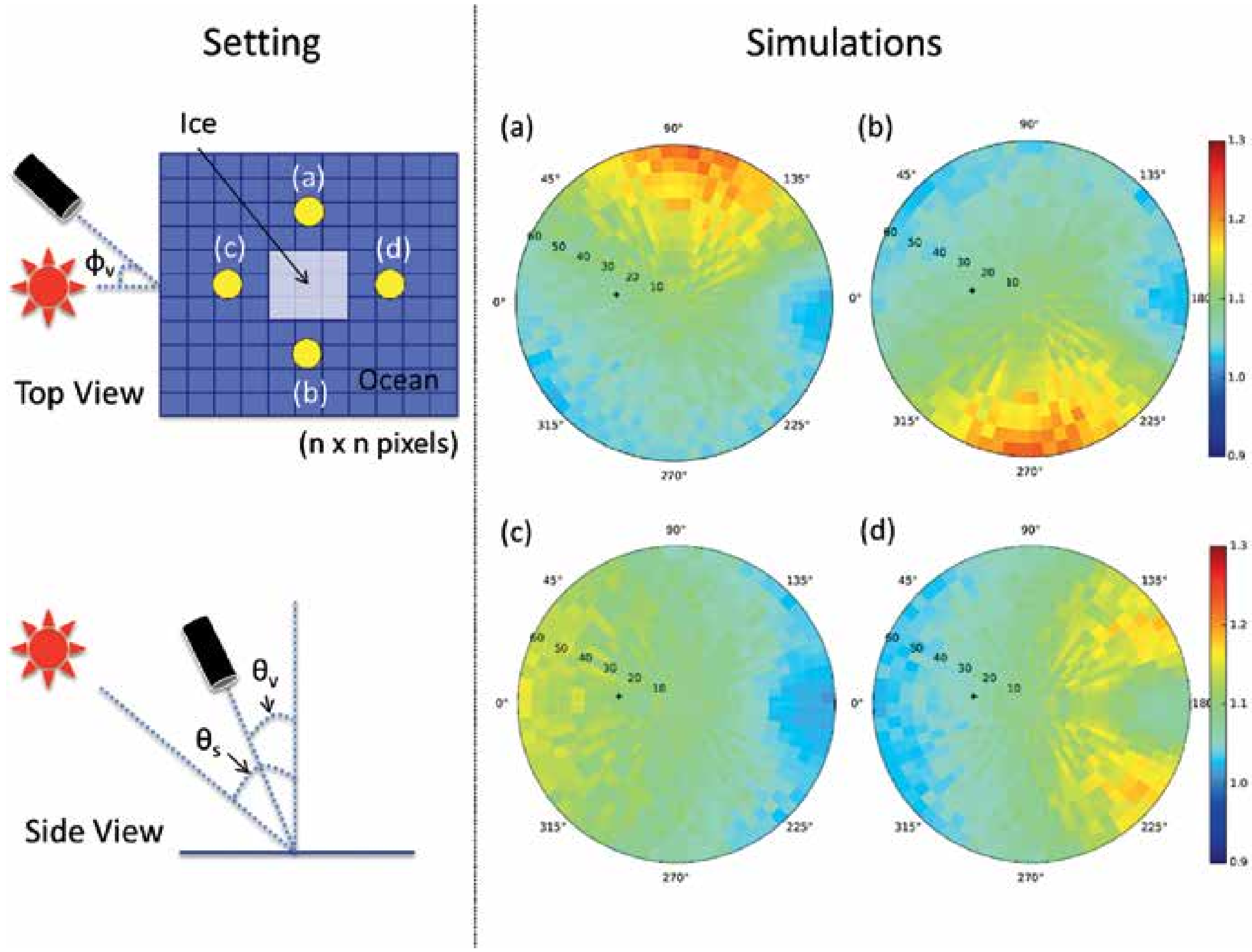


Figure 43. Bidirectional reflectance distribution function (BRDF) at four positions, showing that ρ-TOA is clearly influenced by sea ice.

in different phytoplankton taxa identified using HPLC pigments in the water column. This taxonomic change can be observed in change in phytoplankton spectra as shown in Figure 40.

Two underwater gliders were deployed during the *Amundsen* cruise to measure bio-optical properties and environmental data such as temperature, salinity, nitrate, with high spatial and temporal resolution (Figure 41). We observed some interesting features in all of the sensors from 150 to 250 m in the middle of our trajectories. This type of feature can only be seen using a high-resolution instrument such as a glider.

Water column stratification in the surface layer, subsurface chlorophyll maximum, and the corresponding nitrate concentration can clearly be seen from Bio-Argo float data (Figure 42). Autonomous platforms such as gliders and floats are not only useful for capturing high resolution physical and bio-optical properties but also useful for matchups with ocean color data.

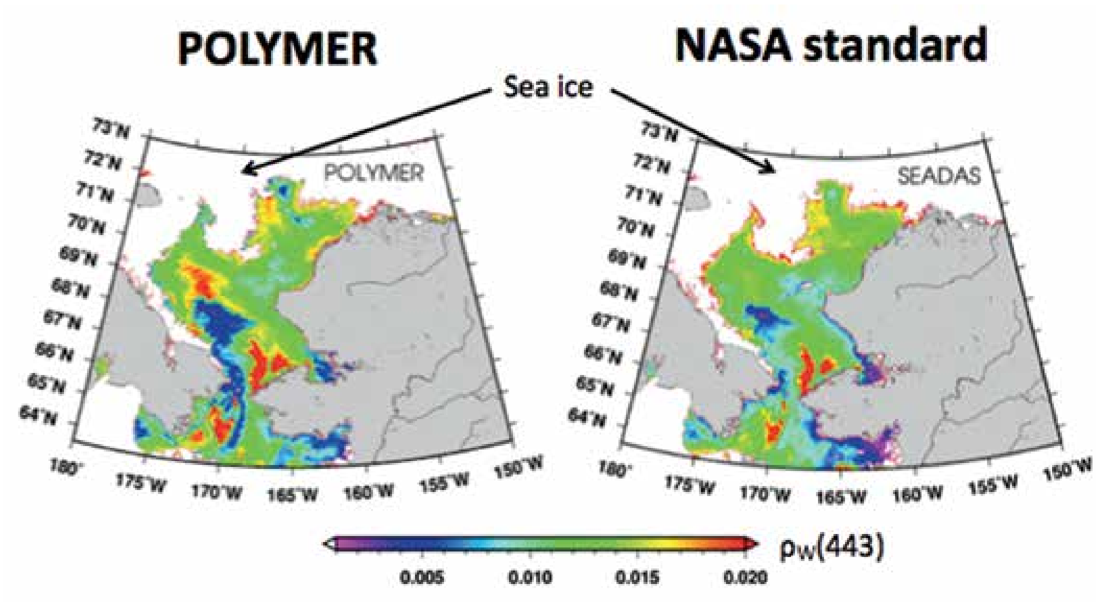


Figure 44. Comparison of the results of the application of NASA and POLYMER algorithms.

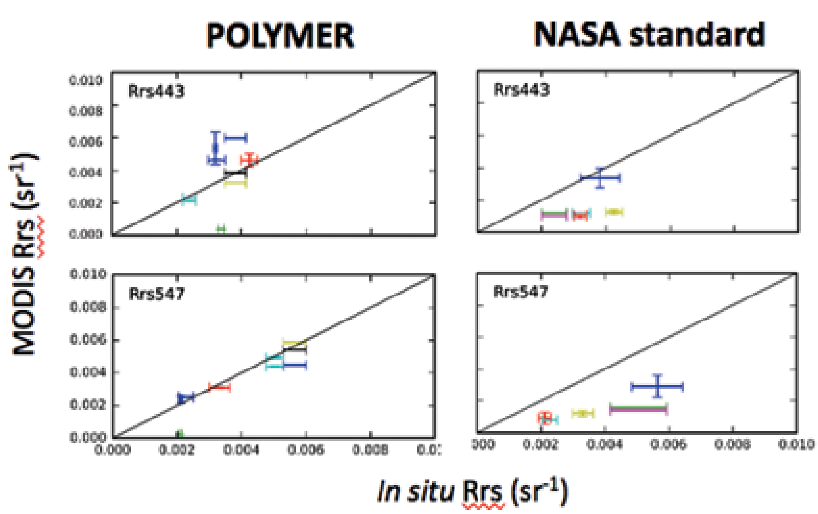


Figure 45. Matchup analysis within 3-hour time window.

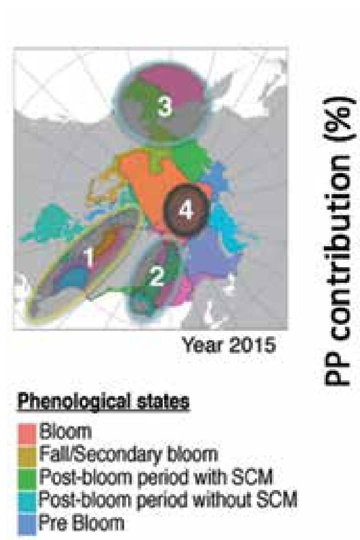


Figure 46. Phenological states of the phytoplankton bloom (2015).

3D radiative transfer simulation was used to simulate reflectance at the top of the atmosphere and evaluate the contamination due to sea ice. Atmospheric correction algorithms were then applied, simulating ρ-TOA for surface including water and ice. ρ-TOA is clearly influenced by sea ice (Figure 43), the magnitude of this effect is dependent on geometry of sun and sensor. This information will be useful to reduce contamination due to sea ice.

Atmospheric correction algorithms were applied to Aqua/MODIS data. High reflectance was found along the ice edge when using NASA standard can be seen along the ice edge. This high reflectance was not observed when using POLYMER algorithm

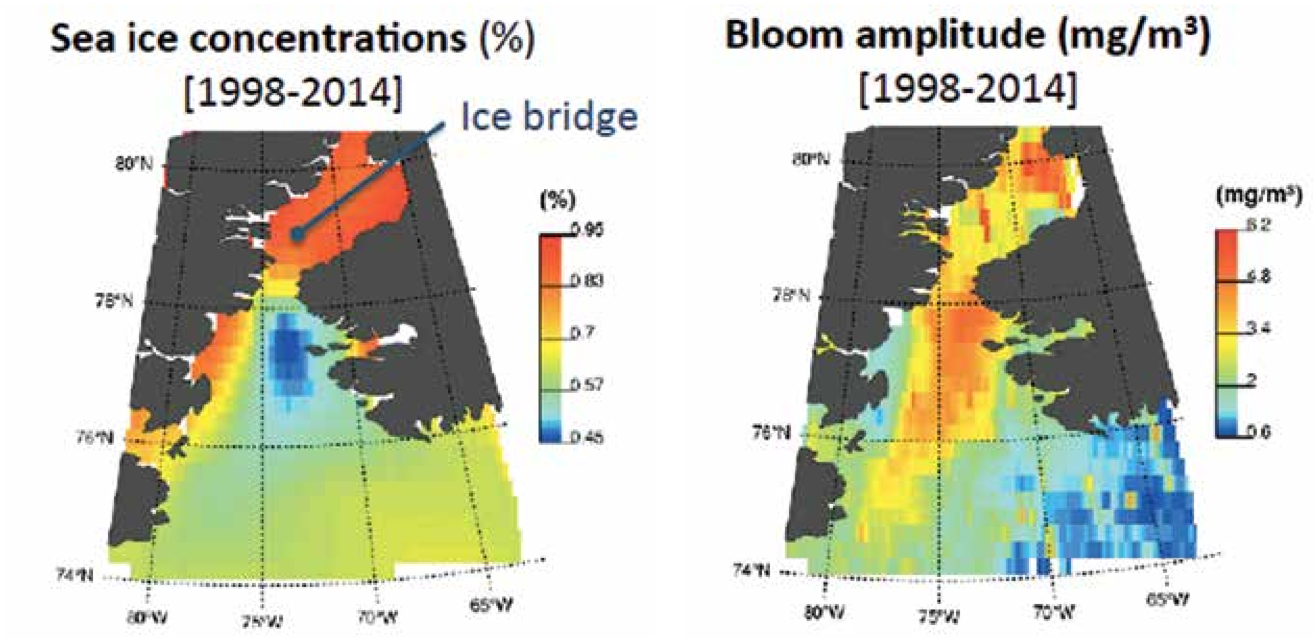


Figure 47. Sea-ice concentration and primary production in NOW (adapted from Marchese et al. 2017). © Springer-Verlag Berlin Heidelberg 2017.

(Figure 44). It is noted that some significant differences in water reflectance for oceanic water were also observed. This was confirmed by match-ups, suggesting that the performance of POLYMER is better than that of NASA standard algorithm, especially for icy waters (Figure 45) and that contamination of water-leaving radiance fields due to sea ice can be reduced using POLYMER.

Long term ocean colour is used to document trends in phytoplankton physiology and primary production. In the early spring, majority of PP is dominated by surface phytoplankton, whereas subsurface phytoplankton make a larger contribution in the autumn, during post-bloom conditions (Figure 46).

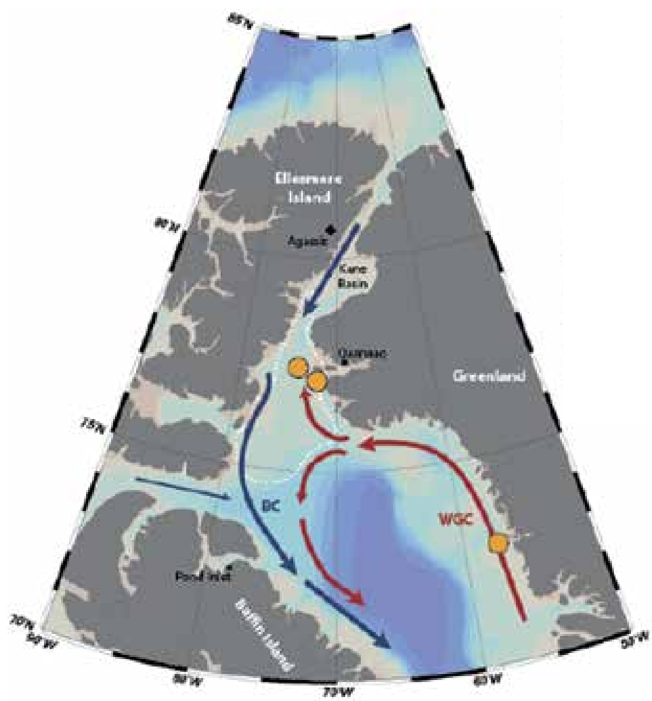


Figure 48. Location of the cores collected from the NOW (two upper yellow dots) and along the western Coast of Greenland (yellow dot at bottom of image - courtesy Audrey Limoges).

Work Package 5: Spring bloom in the past (Paleoceanography)

The objective of this work package was to study the productivity and the effect of sea ice, ice sheets, ocean circulation and nutrient on it through time.

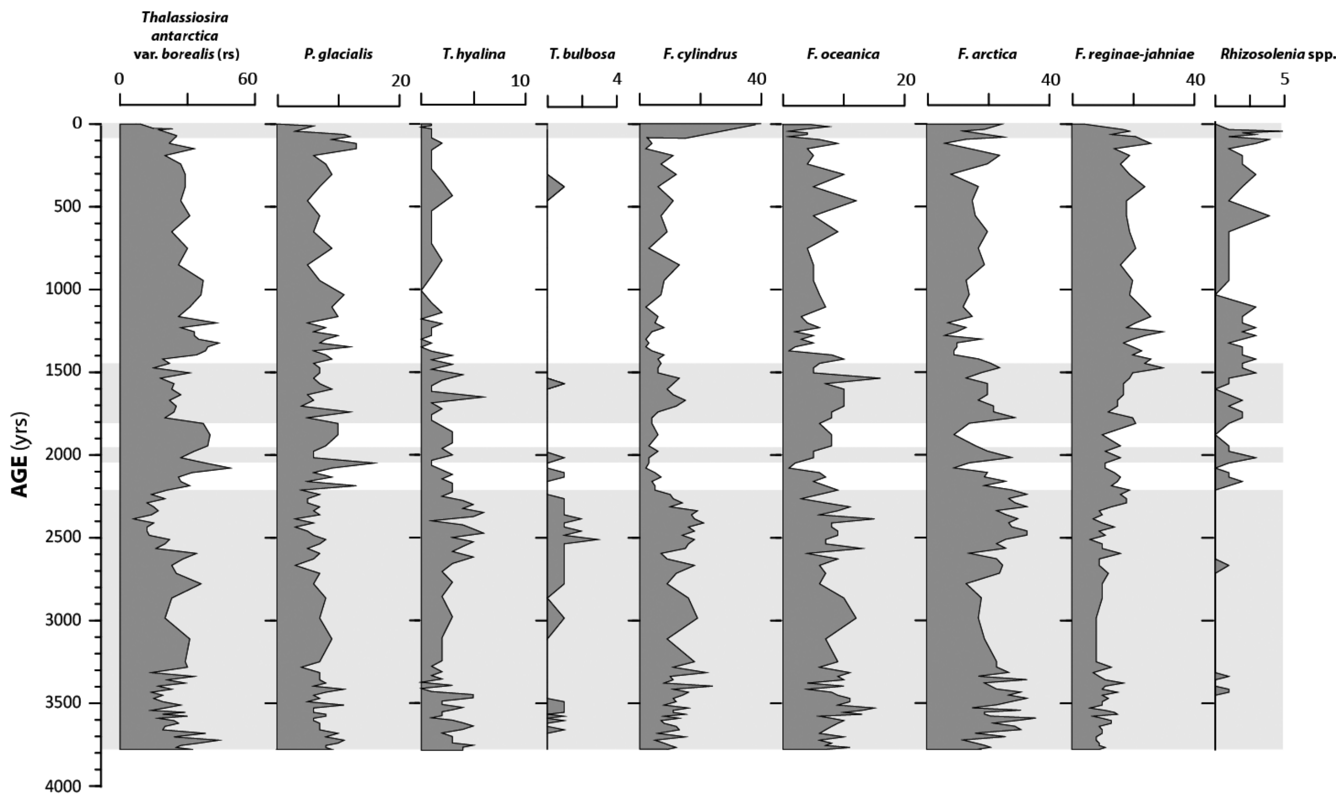


Figure 49. Relative abundances of diatom species.

The evolution of the ice sheet over the last 11,000 years showed a decrease over time until the Holocene thermal maximum (HTM) (4-7,000 years), and then a cooling in the neoglaciation, which is supported by diatoms samples from the northern Baffin Bay. CASQ cores were collected onboard the Amundsen in various locations in Baffin Bay. The sediment composition in these cores can be linked to that of from Greenland glaciers. IP25 and other biomarkers were explored to grasp the organic matter export sources.

The North Water Polynya (NOW) is an area of recurrent low sea ice concentration (Figure 47).

An ice bridge that keeps Nares Straight ice free and highly productive, is becoming increasingly less stable and may have an impact on the NOW formation. Two cores were collected from the NOW region and a core from the Greenland area (Figure 48) to study the influence of different water masses. By studying the relative proportions of the productivity of different diatoms in the core layers, researchers can determine whether the area was ice covered, a Marginal Ice zone or open water.

Results show a decline in the diatom assemblages in the NOW region 2500 years ago and again 2200 years ago, which translates into a decrease in production. The ice condition was unstable between 1300 and 2300 years ago. Reconstructed of sea and atmospheric temperature show variability, with the lowest temperature values matching the period when there are no records of indigenous activity in Greenland. 2200 to 3700 years ago there was high PP and diatom diversity (Figure 49). This was followed, 2200-1000 years ago, by a major shift in productivity and a period of instable ice conditions, probably related to an unstable ice bridge, as evidenced by low PP

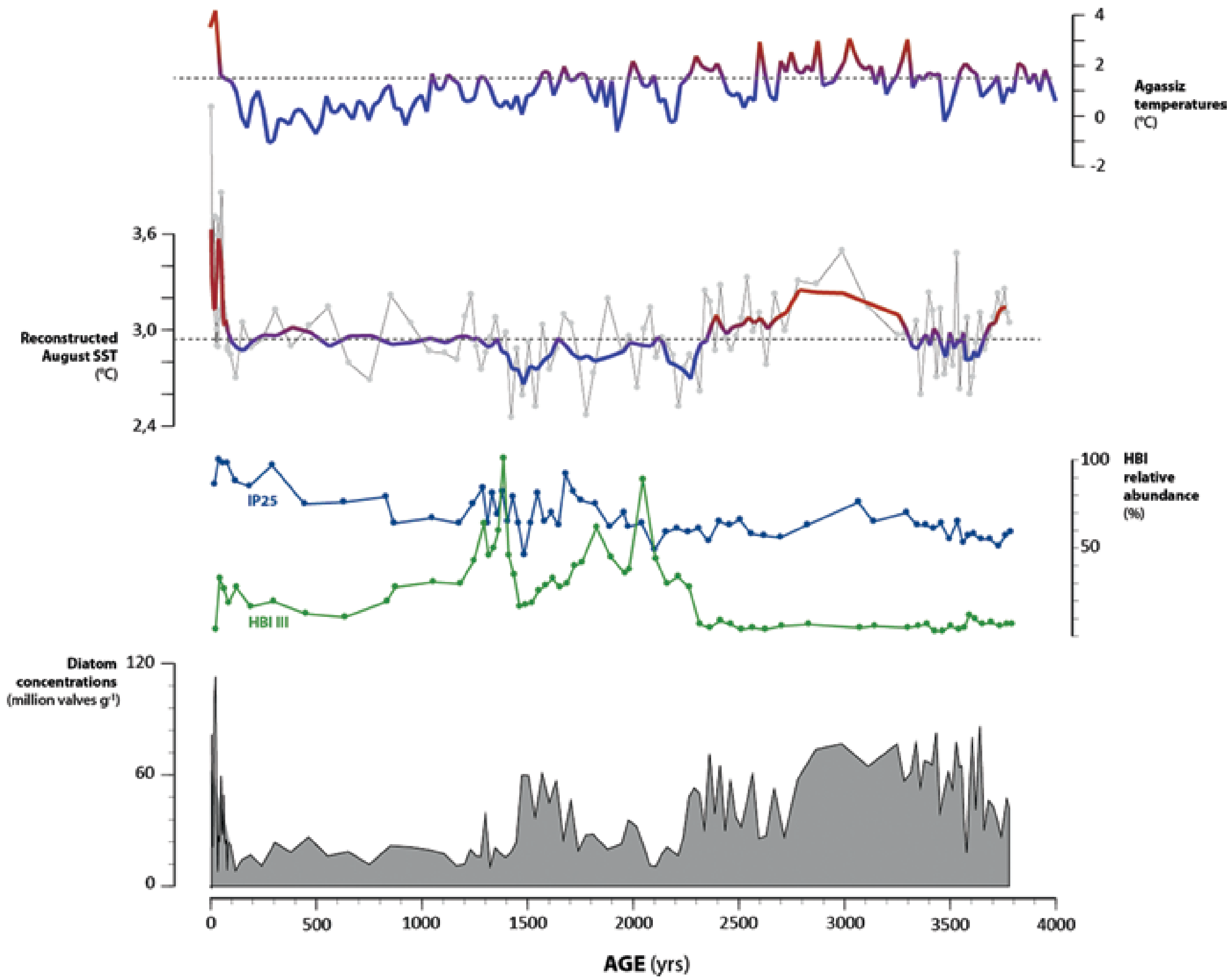


Figure 50. Determination of SST, productivity and ice conditions from diatom abundance.

and diatom diversity. One hundred years ago, the ice bridge grew higher and more unstable. The current period, over the last 100 years, is characterised by an increase in sea surface temperature and an increase HBI which may match the unstable conditions found in the second periods (Figure 50). Note that the sea surface temperatures are overestimated through this approach due to the reference diatoms coming from temperate regions. Preliminary results of dinoflagellates have been processed but need to be analysed.

Work Package 6: Spring bloom in the future (Modelling)

Primary production is limited by light and nutrients. The presence of sea ice and snow controls the availability of light and therefore, the onset of the phytoplankton bloom. As ice melts and the bloom progresses, the water column becomes stratified and nutrients become limited. Before sea ice begins to form in the autumn and there is still sufficient light, the mixed layer deepens and nutrients become available for a fall bloom. An illustration of mean annual primary

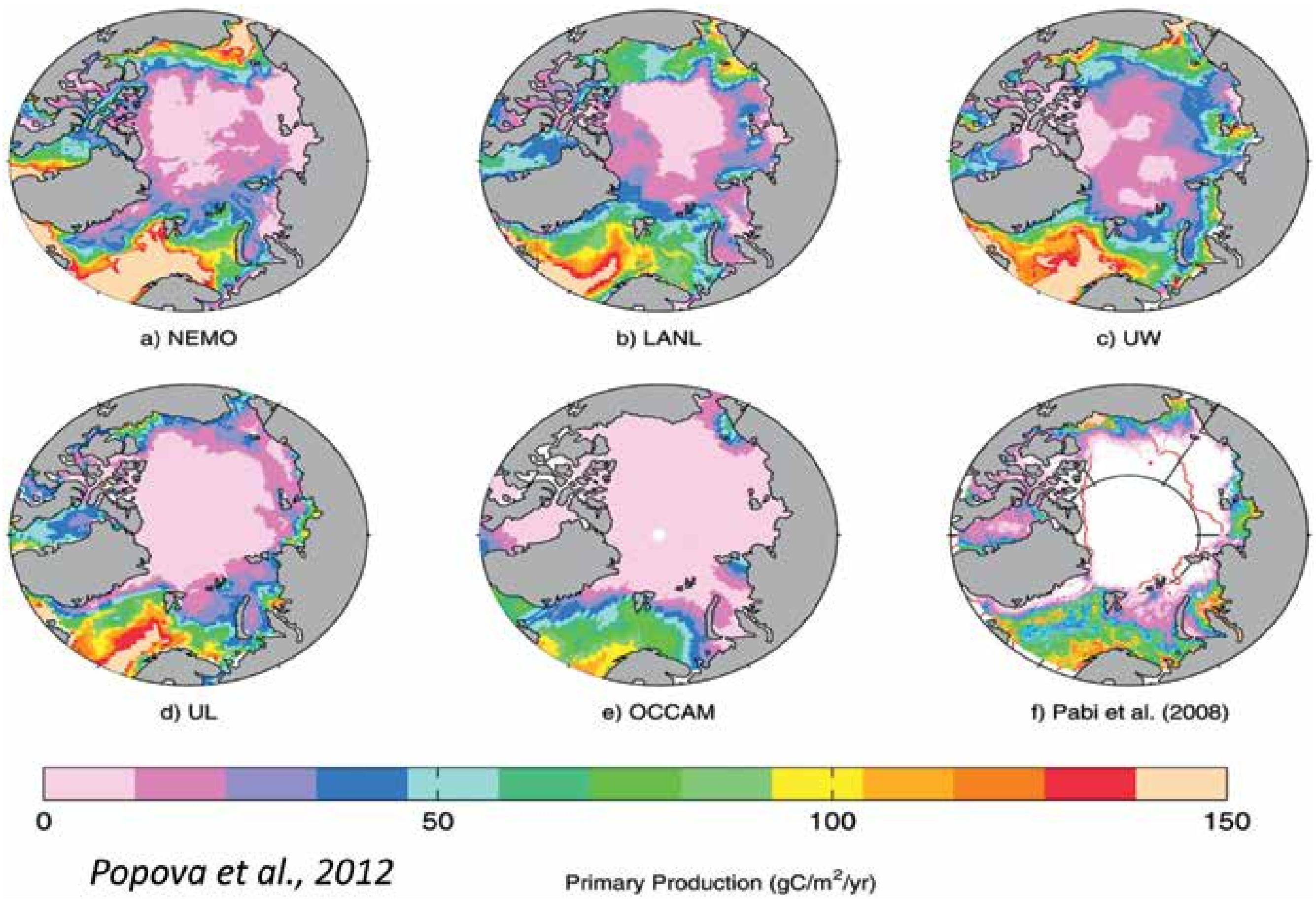


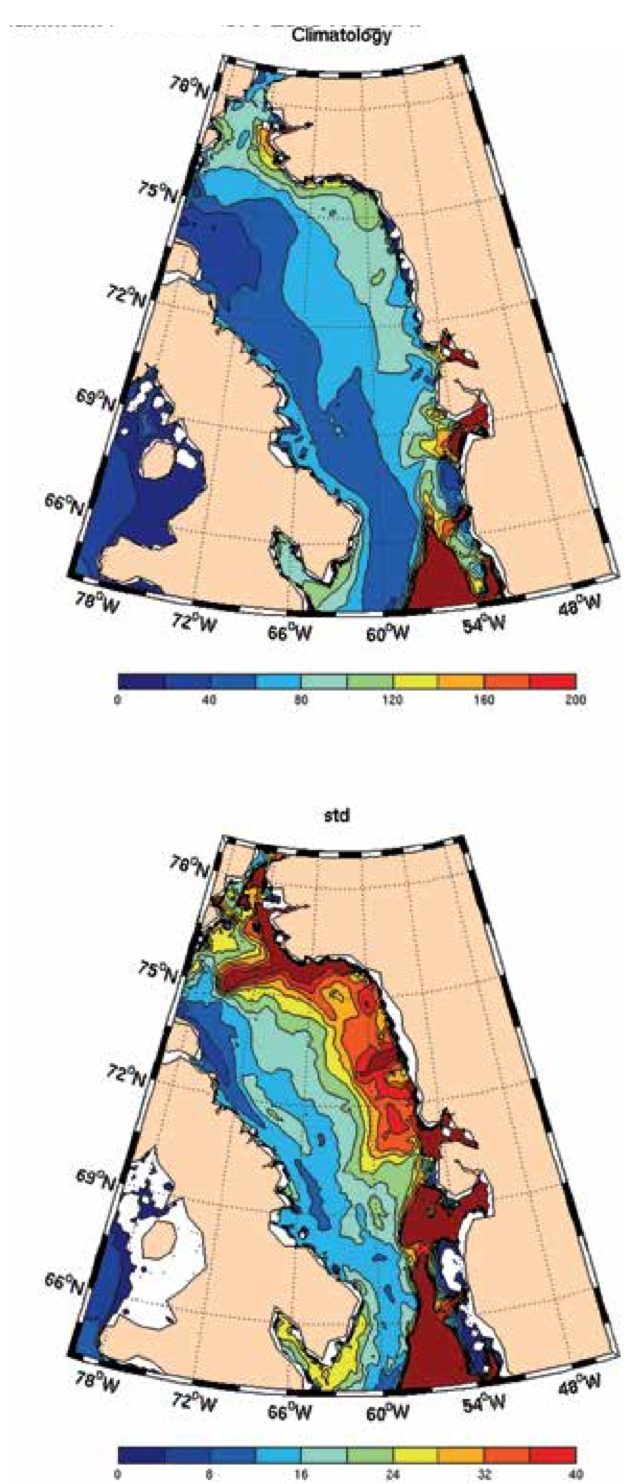
Figure 51. Mean annual primary production (g C m^{-2} y^{-1}) in the water column using different models. From Popova et al. 2012.

production in the water column using different models is shown in Figure 51.

Other problems include the (de)coupling and mismatch between primary and secondary production, particle formation, carbon flux and the (de)coupling between pelagic and benthic ecosystems, all of which have implications for the food web. The objectives of this work package were to gain a better understanding of the physical processes involved in mixing and stratification (1D model), to describe the impact of the climate and ocean (3D model), and to infer the potential impact of sea ice decline for the next 50 years (IPCC simulations).

GreenEdge ice camp data (ice concentration, ice thickness, snow thickness, meltpond) were used to model radiative transfer schemes and retrieve underice PAR. These data were compared to in situ under ice PAR observations (Vancopenolle and Lebrun). The onset of the bloom was examined using the NEMO PISCES model and data from Qikiqtarjuaq (Memery and Olivier). Preliminary results using standard PISCES simulations show that the bloom is mainly composed of nanophytoplankton, which doesn't match field observations. The timing of the bloom in the model requires adjustment to match field observations.

Physical modeling includes mixed layer depth and sea ice conditions (Houssais, Herbault, et al) for Baffin Bay and the Qikiqtarjuaq region. Maximum



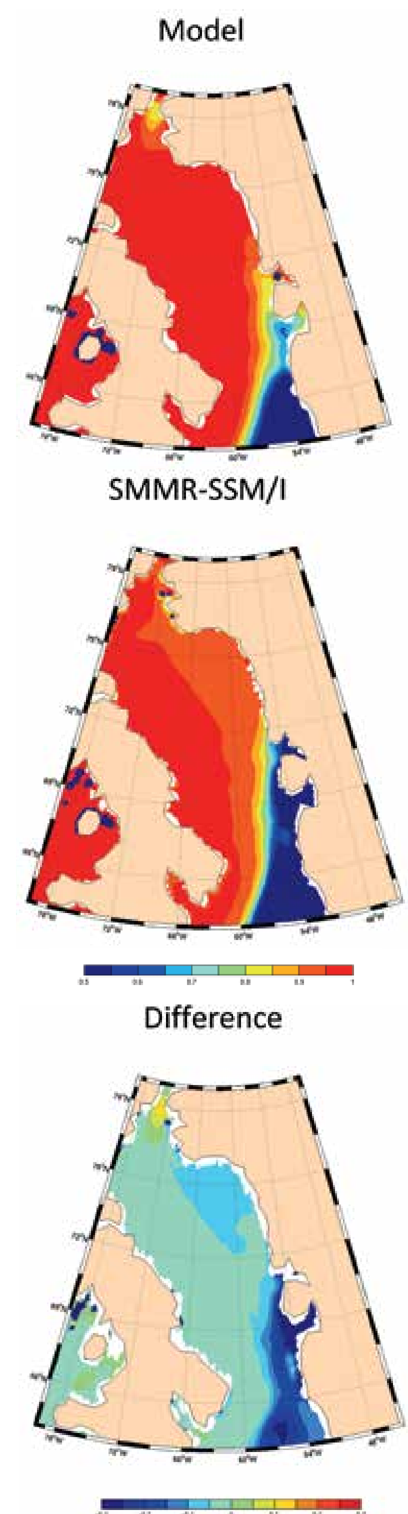


Figure 52. Maximum mixed layer depth in Baffin Bay (climatology 1979-2014).

Figure 53. Winter (January-March) sea-ice concentration (Climatology 1979-2014).

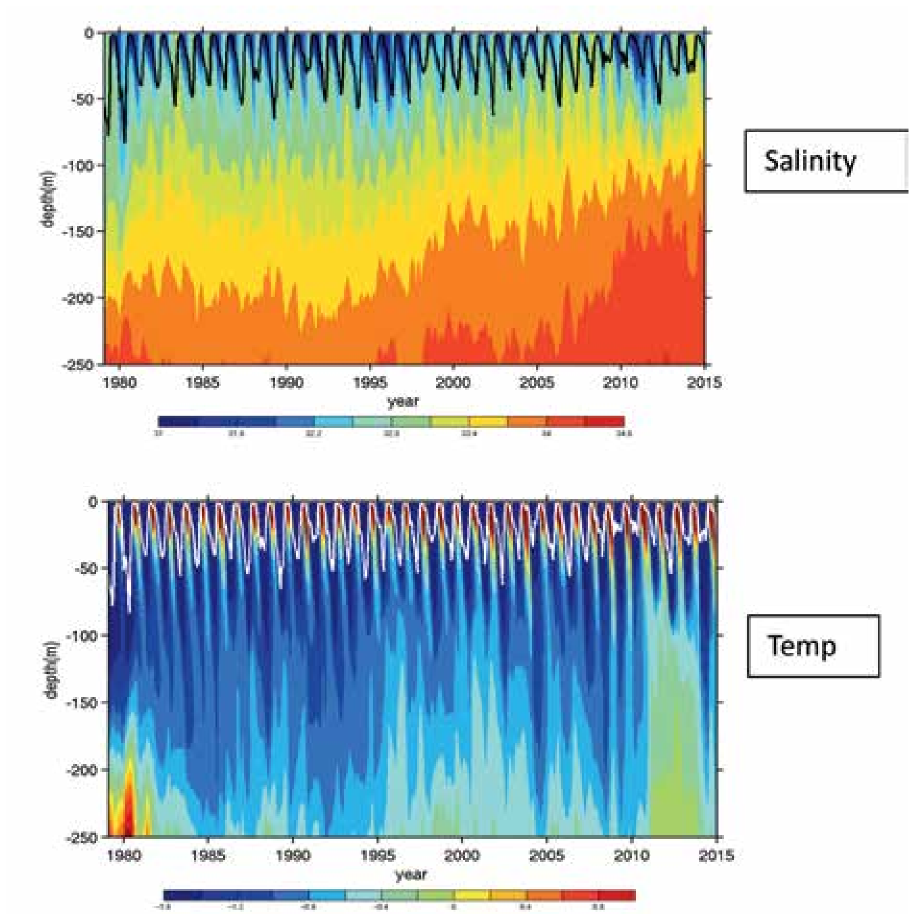


Figure 54. Temperature and salinity near Qikiqtarjuaq (climatology 1979-2014).

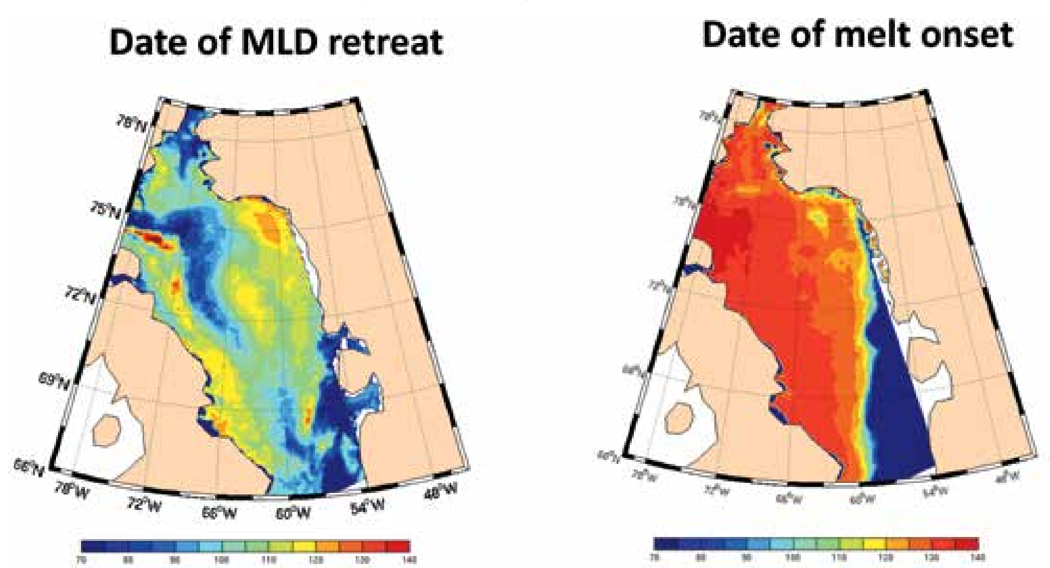


Figure 55. Comparison of dates of mixing layer depth retreat and onset of melt.

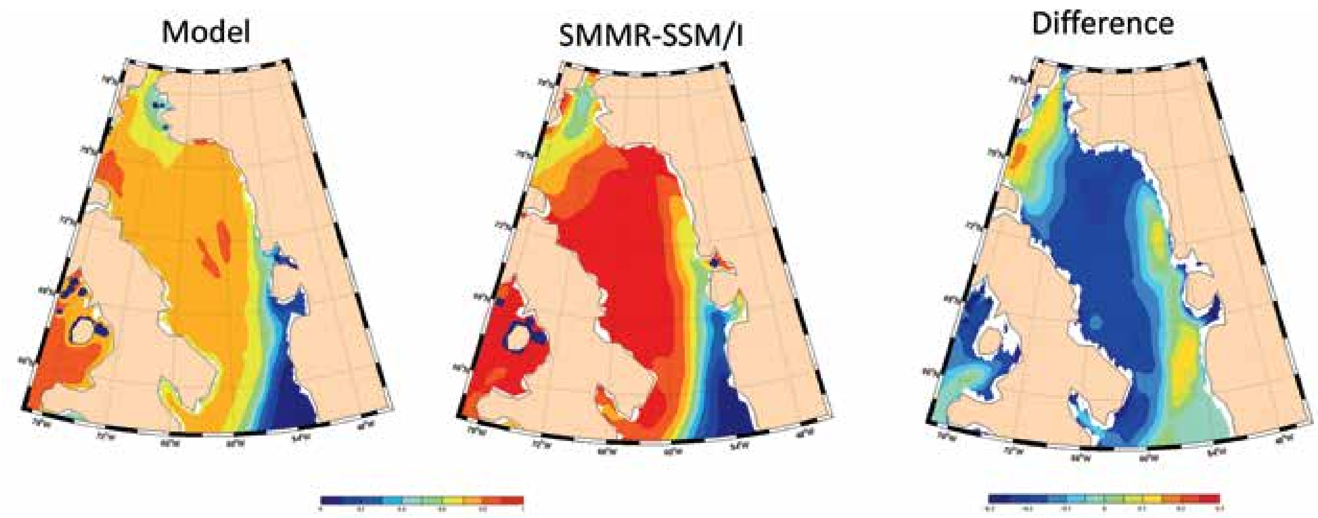


Figure 56. Spring (April-June) sea ice concentration in Baffin Bay (climatology 1979-2014).

mixed layer depth (climatology 1979-2014) shows a regional contrast with deeper layers in the eastern region (Atlantic waters compared to the western region (Arctic waters) (Figure 52).

Preliminary results for sea ice concentration in January-March (climatology 1979-2014) show good agreement between the model and observations with regard to the winter sea ice edge. Inner sea ice concentration is slightly overestimated by the model (Figure 53).

In western Baffin Bay (Qikiqtarjuaq region, Maximum mixed layer depth < 100 m), models showed positive trends for salinity, a decadal variability in temperature in the Atlantic water layer and mixed layer deepening limited by the strong upper salinity stratification (Figure 54).

In western Baffin Bay the mixed layer retreat is triggered by input of surface buoyancy from the Arctic fresh water outflow and occurs 10-30 days before sea ice melt (Figure 55).

The model showed an earlier sea ice retreat and lower ice concentration in central Baffin Bay (Figure 56). There is still a need to validate the sea ice – mixed layer dynamics phasing with relevant 2016 GreenEdge ocean observations.

In terms of primary productivity at the pan-Arctic scale, 3D pan-Arctic simulation using NEMO3.6/LIM3.PISCES is ready to be done and analysis of the climate run are in process. However, more 1D sensitivity tests and calibration need to be done. The Qikiqtarjuaq data set is proving to be extremely useful for calibration (optics, PICES), particularly during the period of sea ice melt and bloom onset. Several issues that need to be addressed including the presence of phaeocystis, which is related to an absence of diatoms, the impact of zooplankton (copepods) on the bloom and the flux of sea ice algae to the benthos.

Work Package 7: Social and health issues related to changes in marine resource availability and quality

Food insecurity is associated with a number of diet quality and health indicators such as lower consumption of vegetables, fruit, grains and dairy products, a greater percent of energy from high-sugar foods, higher RBC trans-FA and lower hemoglobin levels. Conceptualizations of Inuit

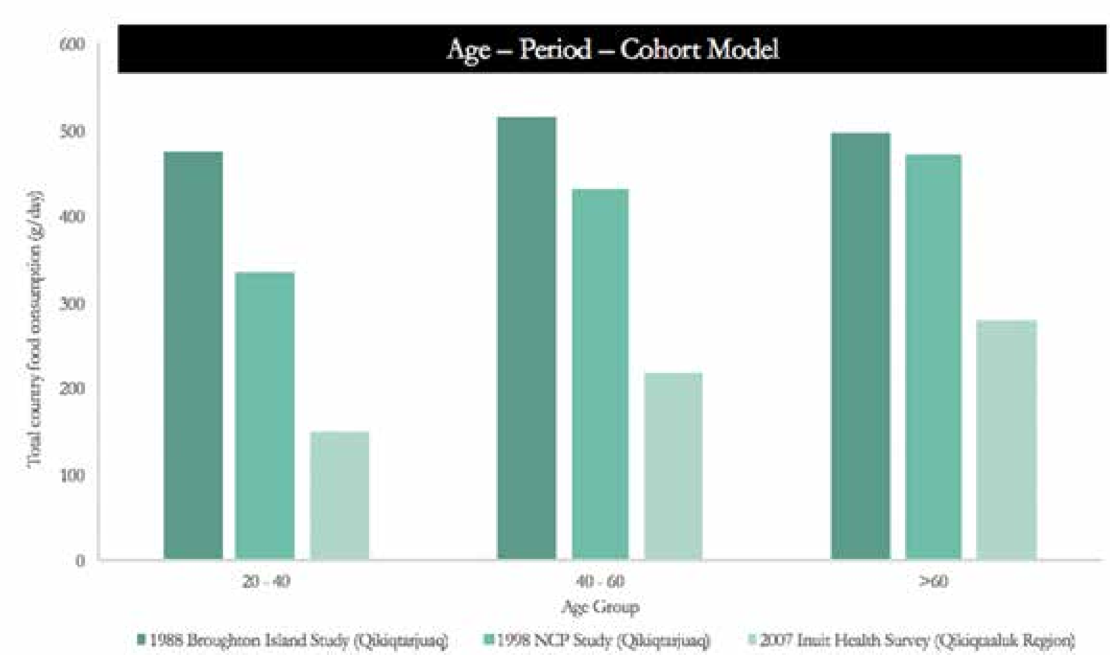


Figure 57. Country food consumption by women in Qikiqtarjuaq as documented in three different studies.

health that emphasize biomedical health metrics fail to capture holistic understandings of health and wellness in the Inuit context, things like education, culture and language, which are effectively the "social determinants" of health. The demographics of Qikiqtarjuaq, NU are similar to many other communities on the coast of Baffin Bay. Over half of the 600 people who live in the hamlet are children and the average age of the inhabitants is 26 years old. Eighty-six percent of the population depends on hunting and fishing for part of their diet, making them extremely sensitive to changes in the marine environment due to warming climate and a longer ice-free season. Over the past 30 years, the community has

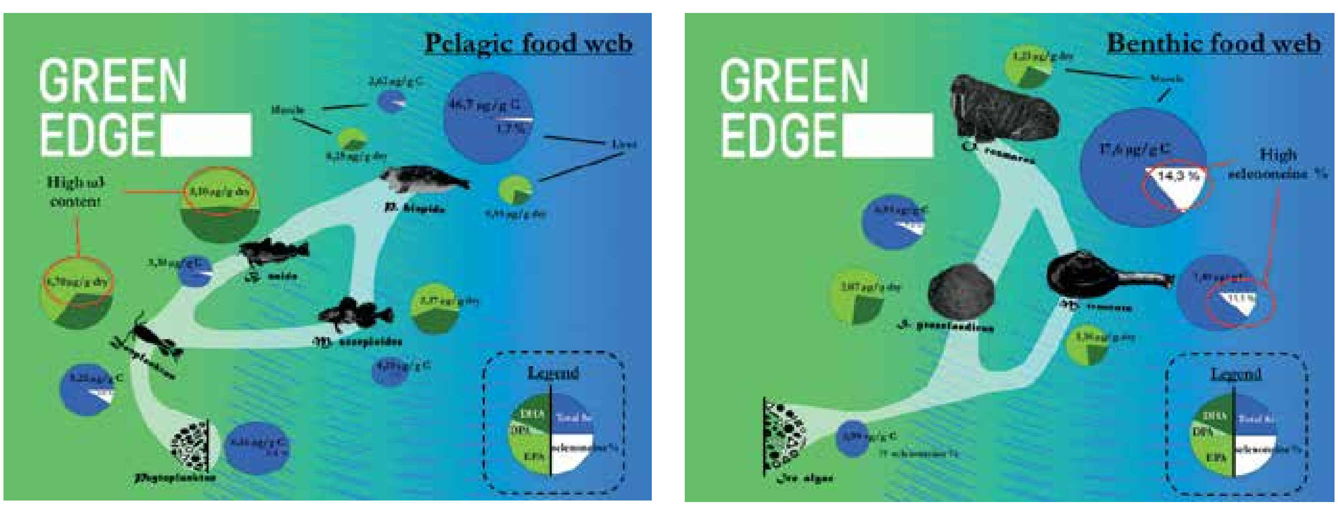


Figure 58. Nutrient flow in the pelagic and benthic food webs in Qikiqtarjuaq.

been part of several health studies, which provides a good historical record of anthropological and nutrition data. These studies show that the consumption of country food has declined over this period (Figure 57).

There are four overlapping components in food security: access, quality, quantity/availability and food preferences/use. An investigation of the distribution of fatty acids, lipids, and selenium/selenoneine (antioxydant and detoxification of methyl-mercury) revealed elevated omega-3 levels in zooplankton and cod within the pelagic food web. Total selenium levels were found in organisms in the benthic food web. In bivalves and walrus muscle tissue, important sources of food for the Inuit population, 10-15% of the Se was in the form of selenoneine (Figure 58).

Modelling of the trophic network discriminated between eastern and western Baffin Bay. In the ice-covered western ecosystem, primary production was distributed through all herbivorous groups, there was low exudation of dissolved organic carbon (DOC) and all prey contributed significantly to their predator's diet. These conditions favoured the creation of reserves and export. Eastern Baffin Bay was characterized by open water and an advanced bloom. The food web was organized to sustain the needs of *Calanus* spp. and bacterial production. There was high DOC exudation, a simulated microbial loop and a linear carnivorous food chain. The ascendant food web in the east featured efficient transfer and less export of carbon.

Intergenerational and inter-cultural consultations with the Hunter and Trapper Organizations and members of the local populations in Qikiqtarjuaq (2016), Pangnirtung (2017) and Clyde River (2017) provided Inuit knowledge on a vast variety of subjects such as climate change, security on the ice, hunting resources, food preference and availability and invasive species and 2016. A 13-minute documentary was produced documenting the co-consultations and interviews.

CONCLUSION

Judging from the results of the ongoing analyses of GreenEdge data, we deem the project to be a success. We correctly identified the spatio-temporal 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. We will increase our modelling efforts to predict future changes to Arctic marine ecosystems and the impact that they will have on the pelagic and benthic food chains, including the human population.

The unexpected *Phaeocystis* spp. bloom observed during the *Amundsen* cruise confirmed the presence of important changes in Baffin Bay, which must be further studied.

A special issue of Frontiers in Marine Science will be dedicated to the GreenEdge project, with submissions opening in April 2018. Consortium members have indicated their intention to publish close to 120 scientific articles using GreenEdge data over the next 24 months.

Our communication, outreach and food security projects have impacted both Inuit and non-Inuit populations and we hope to maintain the excellent relationship that we have developed with the people of Qikiqtarjuaq and other communities on Baffin Island.

ACKNOWLEDGEMENTS

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PUBLICATIONS

Amiraux, R., Belt, S.T., Vaultier, F., Galindo, V., Gosselin, M., Bonin, P., Rontani, J.-F. 2017. Monitoring of photooxidative and salinity-induced bacterial stresses in Arctic using specific lipid tracers. Marine Chemistry 194: 89-99.

Calleja, M.L., Kerhervé, P., Bourgeois, S., Kędra, M., Leynaert, A., Devred, E., Babin, M., Morata, N. 2017. Effects of increase glacier discharge on phytoplankton bloom dynamics and pelagic geochemistry in a high Arctic fjord. Progress in Oceanography https://doi.org/10.1016/j.pocean.2017.07.005 (July 2017).

Galindo, V., Gosselin, M., Lavaud, J., Mundy, C.J., Else, B., Ehn, J., Babin, M., Rysgaard, S. Pigment composition and photoprotection of Arctic sea ice algae during spring, Marine Ecology Progress Series 585:49-69.

Goyens, C., Marty, S., Leymarie, E., Antoine, D., Babin, M., Bélanger, S. 2018. High angular resolution measurements of the anisotropy of reflectance of sea ice and snow. Earth and Space Science. doi: 10.1002/2017EA000332.

Lowry, K.E., Pickart, R.S., Selz, V., Mills, M.M., Pacini, A., Lewis, K.M., Arrigo, K.R. (2017). Under-ice phytoplankton blooms inhibited by spring convective mixing in refreezing leads. Journal of Geophysical Research:Oceans, 122. https://doi.org/10.1002/2016JC012575.

Neukermans, G., Oziel, L. Babin, M. Increased intrusion of warming Atlantic water leads to raid expansion of temperate phytoplankton in the Arctic. Global Change Biology (accepted).

Pabi, S., vanDijken, G.L., Arrigo, K.R. 2008. Primary production in the Arctic Ocean, 1998-2006. J. Geophys. Res. 113, C08005, doi:10.1029/2007JC004578.

Popova, E.E., Yool, A., Coward, A.C., Dupont, F., Deal, C., Elliott, S., Hunke, E., Jin, M., Steele, M., Zhang, J. 2012. What controls primary production in the Arctic Ocean? Results from an intercomparison of five general circulation models with biogeochemistry. Journal of Geophysical Research 117, C00D12,doi:10.1029/2011JC007112.

Saint-Béat, B., Maps, F., Babin, M. 2018. Unraveling the intricate dynamics of planktonic Arctic marine food webs. Progress in Oceanography (in press) doi.org/10.1016/j.pocean.2018.01.003.

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

Project Team

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ABSTRACT

This project improves our understanding of how the atmosphere and ocean force sea ice dynamic and thermodynamic processes. Future changes in sea ice will be modeled based on this knowledge and the consequences of this change on various aspects of ecological and geochemical cycles operating across the ocean-sea ice-atmosphere interface will be examined. To accomplish this, the project intends to examine these interacting systems at a range of space and time scales, taking advantage of in situ experimentation (arctic field campaigns), mesocosm (laboratory) studies, and technology development. 1. Macro-scale - Examine the role of regional to hemispheric scale oceanic and atmospheric forces (in both space and time) on sea ice processes. 2. Micro-scale - Investigate exchange processes at the micro- to local-scale of mass and energy across the ocean-sea ice-atmosphere interface and examine the regional variability. 3. Community-Based Monitoring - Continue linking Western science and Inuit knowledge through community-based monitoring programs. 4. Technology - Develop tools to estimate state of the snow/sea ice system using microwave scattering and emission observations, and microwave scattering models and make these tools available to government and industry partners.

KEY MESSAGES

- An anomalously thick and persistent ice pack along the east coast of Canada in spring 2017 created hazardous maritime conditions. Within one sea ice season multiyear sea ice from the Lincoln Sea and Canadian Arctic was advected southward to the coast of Newfoundland. An increasingly mobile Arctic ice pack is increasing ice flux through Nares Strait and releasing more ice hazards towards southern locations.
- Shipping accessibility in the Hudson Bay and Hudson Strait was investigated by characterizing the timing of breakup, freeze-up, and the open water season in offshore and local waters. Offshore ice timing was analyzed using passive microwave-based data for 1980 to 2014, local ice timing near Rankin Inlet, Churchill, Kuujjuarapik/Whapmagoostui, and Salluit was also examined. The four communities had open water periods of 119, 126, 161 and 140 days respectively. The length of open water for the communities has increased over the study period. This could have considerable implications for the people of the study area. Growing shipping accessibility could increase sealift, which could reduce the cost of goods in northern communities and facilitate resource projects and economic growth. For communities, changing ice conditions, weather events, lack of infrastructure and shortage of baseline and real-time information about conditions make travel on the ice and coastal waters less safe.
- Long-term trend in the anomalies in the sea ice drift speeds from October 1979 to April 2015 show that drift speeds have increased across the entire Arctic basin and for all months of the winter period.
- During the past fiscal year (April 2017 – March 2018) we have produced over 39 peer-reviewed publications we have also presented at over a dozen different international conferences, workshops or meetings.
- We have participated in three field programs: SERF winter 2018, CCGS *Amundsen* BaySys Cruise spring 2017, and CCGS *Henry Larsen* BaySys Mooring Field Campaign.

RESEARCH 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 in each of the ArcticNet IRIS marine regions.
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 in these within the ArcticNet marine IRIS regions.
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 system using microwave scattering and emission observations, electro-thermophysical, forward and inverse scattering models 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 several national and international conferences and workshops, this included:

- Polar Data Workshop – Summer 2017
- AMAP International Conference – Spring 2017
- Arctic Frontiers Conference – Winter 2018
- Forum for Arctic Modelling and Observational Synthesis (FAMOS) October 2017, Woodshole Ocenographic Institute, Woodshole, Massachusetts, USA.
- ID Arctic, February 2018, Toronto, Ontario, Canada hosted by the Norwegian Polar Institute
- Bonn, Germany - COP 23 - sea ice and climate change presentation
- As part of Arctic Change 2017 we presented over 10 poster and oral presentations.

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

- Hudson Bay Summit –posters presentations and a keynote presentation on the Hudson Bay IRIS directly to Hudson Bay community members from over 20 communities around the region.
- Churchill MB - presentation on the programs in Hudson Bay
- Minister of Natural Resources - trip to Churchill to discuss climate change impacts on the rail line and port

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

- Science Rendezvous in May 2017, University of Manitoba. Using top research institutions, the annual festival takes science out of the lab and makes its accessible to the public.
- Annual Schools on Board and Fort Whyte Alive – Arctic Science Day in March 2018. 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).
- Churchill Northern Studies Centre (Winter 2017) Students and researchers did presentations for the community on "Sea Ice in Hudson Bay".
- Women in Science – several students and researchers attended schools to discuss the role women can have in science careers.

David Barber has also given multiple media talks on the changing sea ice regime and the postponement of BaySys. In addition he has participated in:

- International review panel member, five-year review of the Alfred Wegener institute (AWI) - March
- CERC meetings in the USA - MIT, Yale, Harvard and Woods Hole (Feb)
- Paris, France - Prix polar photojournalist award committee work (Nov)
- Michigan State University - sea ice and climate change forum (Feb)
- Meeting with Manitoba Hydro Executive Committee for Stakeholder engagement as part of the Hudson Bay IRIS and BaySys (Nov)
- University of Manitoba – Public Climate Change Symposium

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 contributed to a multi-media platform, which includes an e-book that is available on the internet and through the partners of Expedition Churchill. The official launch of this outreach project will be spring 2018.

INTRODUCTION

Throughout the Arctic sea ice is undergoing a decline in concentration, extent thickness and age. Some of these changes and their consequences have been documented and characterized through this ArcticNet Sea Ice project. During this final cycle of ArcticNet, we have continued to develop our understanding between the dynamic and thermodynamic interactions between the ocean, sea ice and atmosphere. As part of our objectives we looked 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. Below we describe some of the previous findings from this project that have been built upon during this last year.

Babb et al. (2016) examined the physical processes that contributed to an ice-free Beaufort Sea during September 2012. Barber et al. (2015) also identified major changes for the ice-associated ecosystem with regard to production timing and abundance or biomass of ice flora and fauna, which are related to regional changes in sea-ice conditions. These changes in sea ice are both affected by and have effects on the physical and meteorological processes operating across the ocean-sea ice-atmosphere (OSA) interface. Lukovich et al. (2015) used case studies to show that when strong winds and strong currents are coincident, the conditions can cause reversals in the motion of sea ice for periods of time longer than 12 hours. The changes in the sea ice also affect how industry must plan and prepare for exploration and development projects involving oil and gas and associated transportation of resources. Barber et al. (2014) documented ice from glacial or thick MYI with keels of more than 30 meters thick and moving faster and in opposing directions to that of the ice pack, which would be hazardous to industry development or transportation in the region.

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 shelf-break 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.

Recently, Barber et al. (2018) examined the heavy ice conditions along the east coast of Canada during the Spring of 2017. These were hazardous conditions for the maritime industry and required the Canadian Coast Guard to pull its research icebreaker, CCGS *Amundsen*, off its scientific cruise to provide ice escort services and conduct search and rescue operations along Newfoundland's northeast coast. They concluded that the increasingly mobile Arctic sea ice cover may increase these ice hazards in the south. Due to the decrease in sea ice, shipping and transportation in the Artic is an area of increased research. Ng et al. (2017) reviews the implications of climate change for Arctic shipping accessibility and examines the feasibility of Arctic routes as realistic alternatives to current southern routes. They conclude that there is a need to improve a framework that can effectively govern and facilitate sustainable shipping in the Arctic. Andrews et al. (2018) investigated shipping accessibility in the greater Hudson Bay area by characterizing the timing of breakup, freeze-up, and the open water season in offshore and local waters.

ACTIVITIES

Amundsen Spring 2017

As part of the related BaySys project we participated in the CCGS *Amundsen* program for 2017. A total of 15 students, staff and PIs from this project and collaborating projects participated in this program. Due to heavy ice conditions the *Amundsen* was diverted from the Science mission. This has delayed the program until 2018. Unfortunately this has affected the ability to include some BaySys data into the Hudson Bay IRIS being published.

Henry Larsen Fall 2017

Due to the cancellation of the *Amundsen* BaySys leg and due to the cancellation of another research vessel cruise to recover moorings, the recovery of BaySys mooring occurred as an opportunistic cruise from CCGS *Henry Larsen* barge. Three oceanographic moorings were recovered and re-deployed on 21-31 October, 2017. Water samplings and CTD casts were executed at each mooring position to determine the vertical thermohaline and hydrochemical structure. Participants included Sergei Kirillov (RA), Vladislav Petrusevich (PhD), Sylvain Blondeau (Tech), and Christopher Peck (PhD).

SERF Winter 2018

Lead by David Barber, Gary Stern and Puyan Mojabi, the experiment ‘Oil in Ice Covered Water Detection’ was run through the SERF facility at the University of Manitoba. This experiment has been run for the past three years. Participants included: Nariman Firoozy, Thomas Neusitzer, Tyler Tiede, Durell Desmond, and David Babb, including collaborations with Soren Rysgaard, Jack Landy, and Marcos Lemes From January to March an oil spill in ice-covered waters experiment was carried out at SERF under controlled condition. The oil was injected beneath a layer of young sea ice and its migration and effect on sea ice evolution was investigated. The radar signature of the oil in ice was measured using a C-band scatterometer and a 500 MHz GPR.

RESULTS

Due to the extensive nature of this project a short selection of results from the past reporting year are presented.

Amundsen 2017

During opportunistic sampling off the northern coast of Newfoundland during the BaySys 2017 rerouting, passive microwave scans, physical sampling and unmanned aerial vehicle (UAV) surveys were collected for three floes between June 6^{th} – 8^{th}. Passive microwave scans were conducted using a surface based radiometer, taking measurements at 19-, 37- and 89 GHz for both vertical and horizontal polarizations. For each floe site, the radiometer was set to scan between incidence angles of 30^{o} to 70^{o}. After radiometric sampling, a UAV survey was flown to capture aerial imagery of the area surrounding the sampled floe.

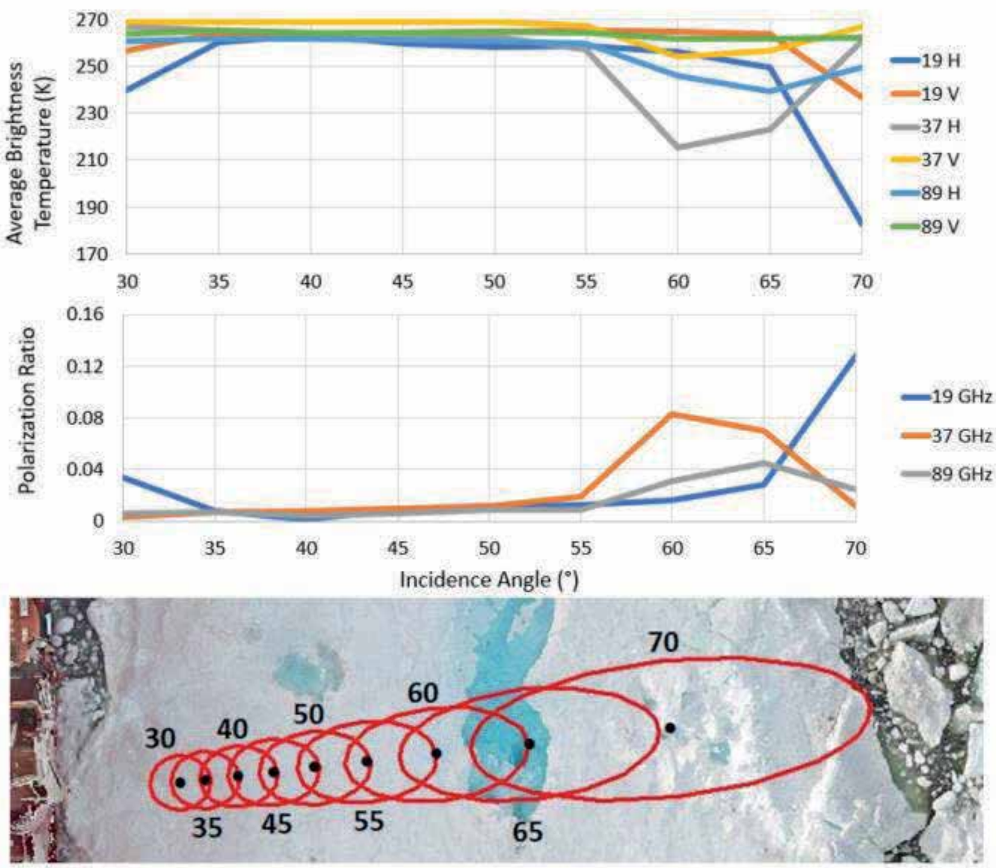

Figure 1. Brightness temperatures (top) and polarization ratios (middle) plotted for each incidence angle, along with the FOV footprint for each angle shown across the scanned floe.

Figure 1 presents average brightness temperatures measured for multiple scans across one of the sampled floes, along with the polarization ratio (a metric often used for radiometric sea ice mapping) and a map of the field of view (FOV) for each incidence angle across the floe. Brightness temperatures and polarization ratios remained relatively uniform between incidence angles of 35 – 55° where areas of smooth ice were included within the FOV. At incidence angles of 60 – 70°, brightness temperatures fluctuate as open ice surface water (melt ponds) and ice ridges are included within the FOV.

UAV surveys were collected to better understand ice characteristics within the surrounding area (Figure 2). This allowed for the creation of an aerial mosaic of RGB imagery, as well as the production of a digital elevation model (DEM) using photogrammetric software based on the overlap of consecutive UAV images. Aerial imagery was processed in ENVI using a decision tree classification scheme to generate high-resolution melt pond and ice concentration maps. In this survey area, floe concentration was determined to be 61% with melt ponds overlapping 2% of the total floe area. The size distribution of floes and melt ponds were also determined, presented in Figure 3. Floe size ranged between 0.03 m^2 to 3963 m^2 and melt pond size ranged between 0.03 m^2 and 112 m^2. DEM analysis showed variable floe surface roughness across the survey, with ice ridges reaching up to 3.1 m (Figure 2). This data was collected in order to compare high resolution ice mapping to coincident satellite-based radiometric data, in order to generate a stronger

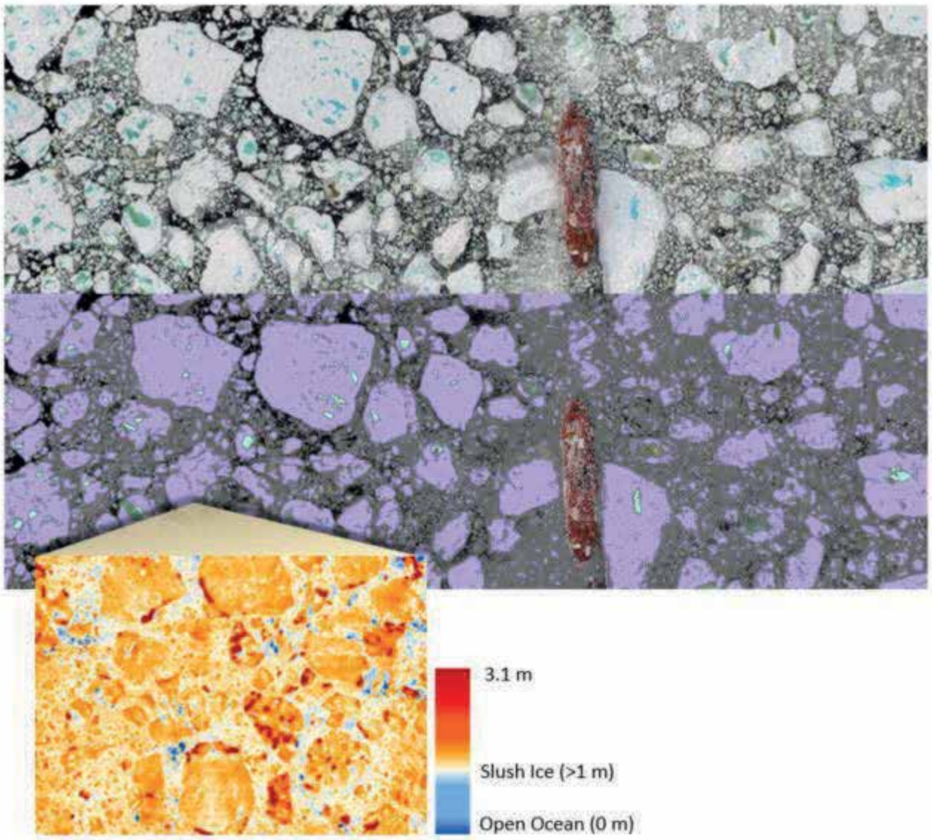

Figure 2. UAV original imagery (top), polygon representation of ice floes and melt ponds (middle) and DEM for a subset of the survey area (bottom).

relationship between measured brightness temperature and ice/melt pond concentration.

Early results from the Hudson Bay Moorings recovered fall 2017

Figure 4 shows a schematic of the three moorings that were recovered on board the CCGS *Henry Larsen*. The location of these moorings is based on the long-term location of ArcticNet mooring AN01 and collaborative work with Manitoba Hydro through the BaySys program over the past decade.

The CT sensors deployed at different depths captured the seasonal changes in vertical thermohaline structure at all three positions. These changes correspond to the impact of different processes such as: the vertical mixing and redistribution of heat from the surface to the deeper layers in autumn; cooling of water column and the following salinity increase due to the sea ice growth in winter; the freshening and warming associated with sea ice melting/river runoff and solar heating in summer (Figure 5).

The effect of atmospheric circulation on vertical thermohaline structure and freshwater content is clearly seen in CT data at NE02. The altering wind forcing led to the shift of the frontal zone formed by fresher coastal water (diluted by rivers' discharge) and saltier basin water. For instance, the considerable freshening observed at NE02 mooring on March 8 and September 3 was associated with low atmospheric

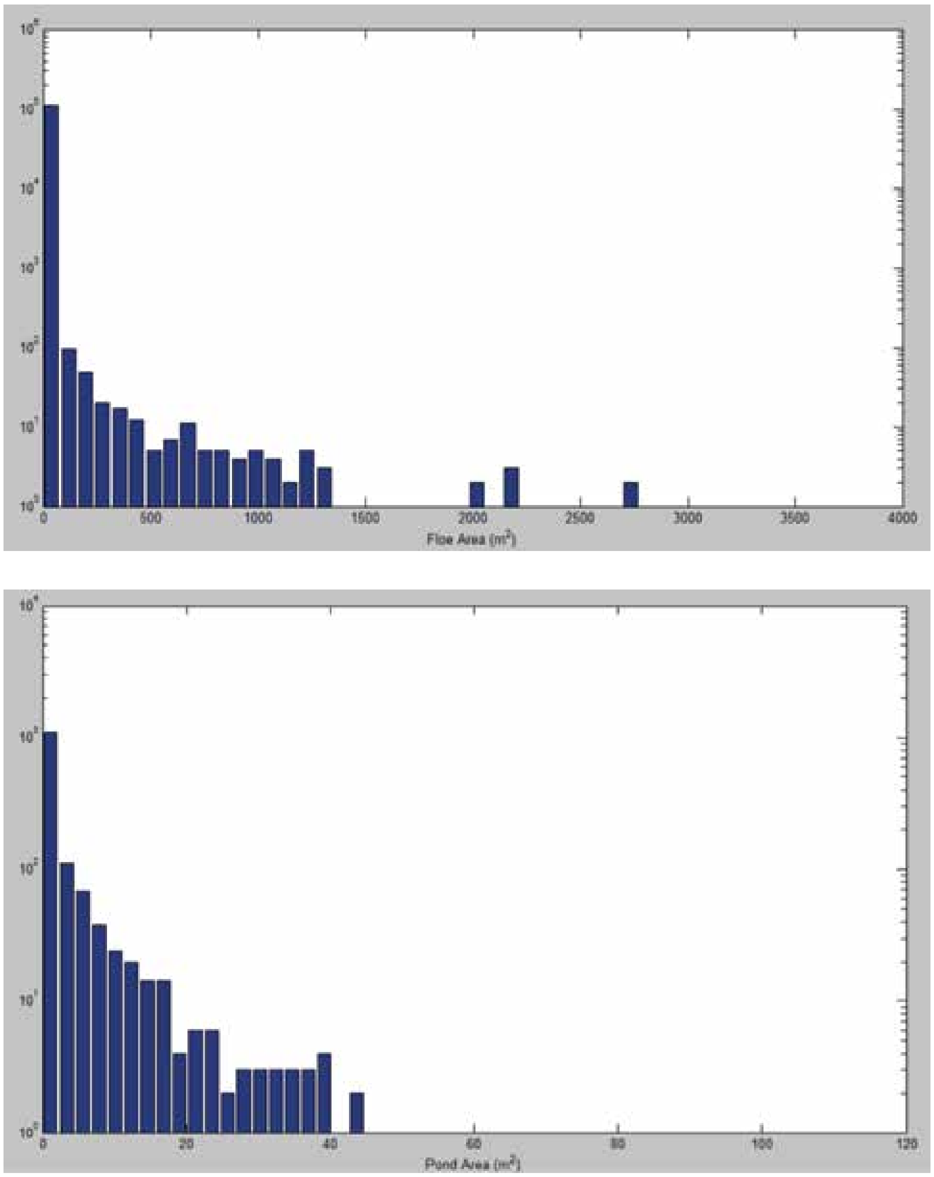

Figure 3. Floe area (top) and melt pond area (bottom) histograms for the survey site.

pressure systems passing over the Hudson Bay. The storm winds resulted in on-shore water transport that blocked riverine waters near the shore and caused abrupt salinity decrease by 1.5-2.0 (Figure 6).

Another piece of important information has been received from the combination of two upward-looking ADCPs: WorkHorse 300 kHz by RDI deployed near the sea floor and Signature 500 kHz by Nortek at AN01 and NE03. Both instruments provided the continual records of water dynamic in entire water column with 15 min recording interval. Moreover, Signature 500 was equipped with 5th vertical beam that allowed measuring the wave heights and directions as well as the draft of ice throughout the full seasonal cycle (Figure 7).

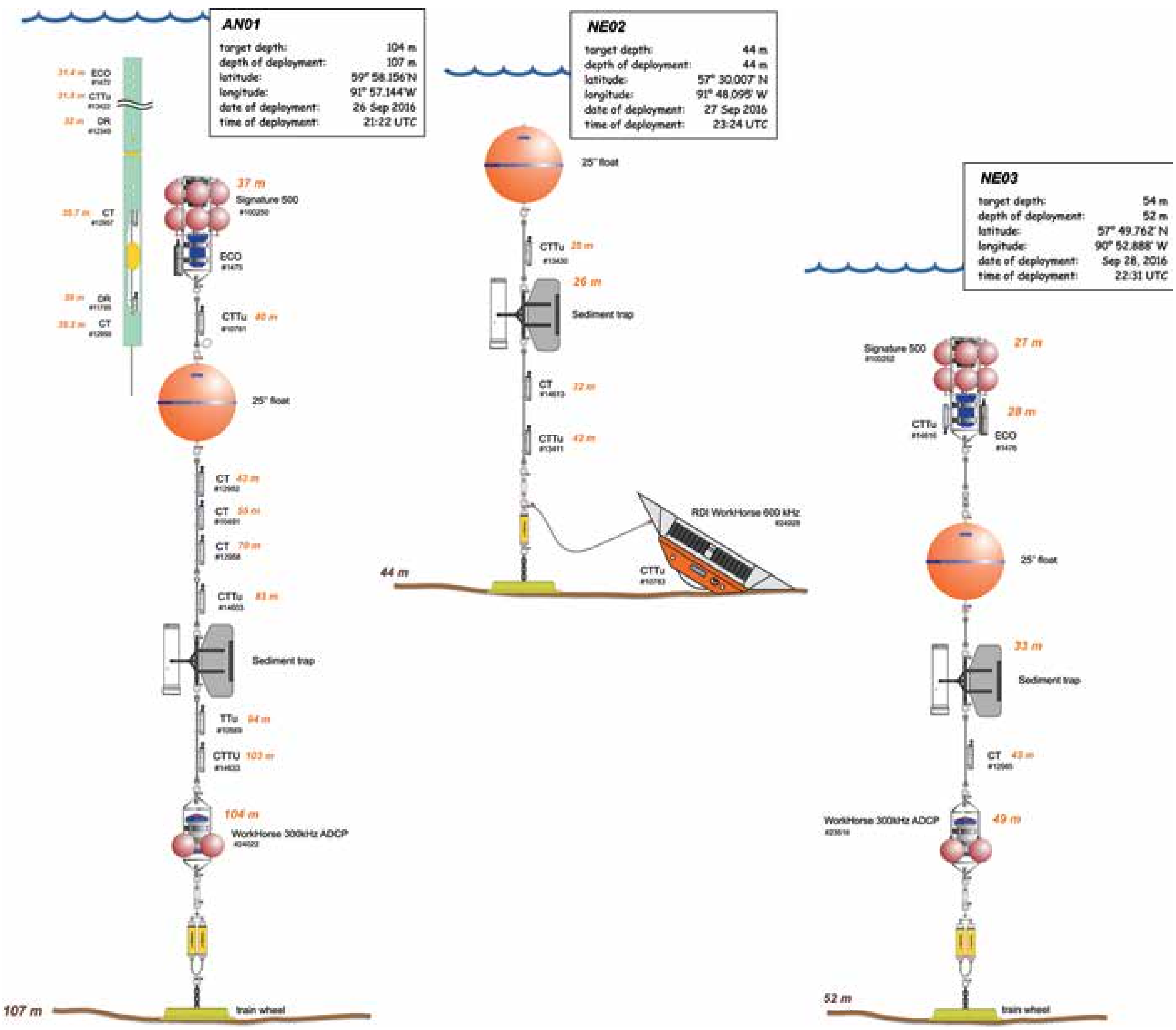

Figure 4. AN01 (Churchill shelf), NE02 (Nelson Outer Estuary) and NE03 (Nelson River outer shelf) mooring configurations as recovered.

SERF Winters 2018

An experiment on crude oil injection in young sea ice was carried out at the SERF facility on the University of Manitoba campus from 2016-2018. Through this experiment, it was shown that the binary detection of oil through the measured normalized radar cross section (NRCS) data (collected by a C-band scatterometer) was possible via retrieving the oil spill volume fraction. This retrieved volume fraction has the potential to be utilized as an auxiliary way to estimate the amount of the spilled oil, knowing the sea ice thickness in the area, and the radar footprint at which the drop in the NRCS value was observed.

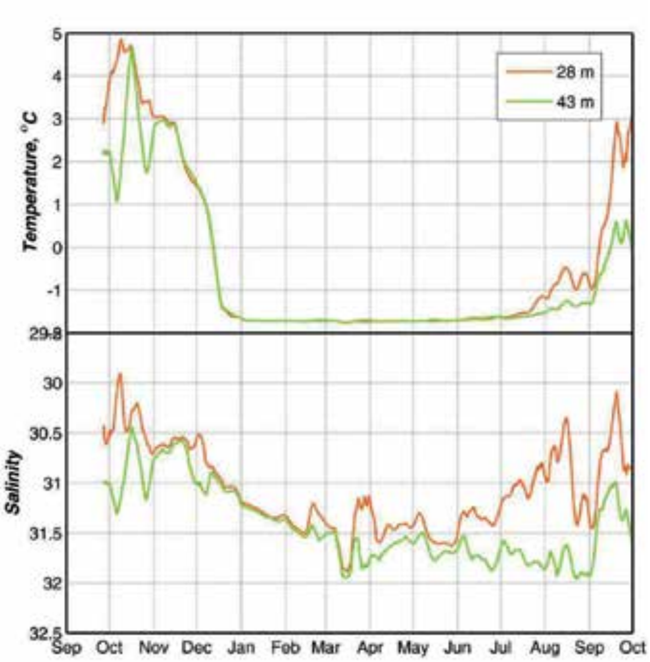

Figure 5. The one-year evolution of vertical thermohaline structure at NE03 mooring.

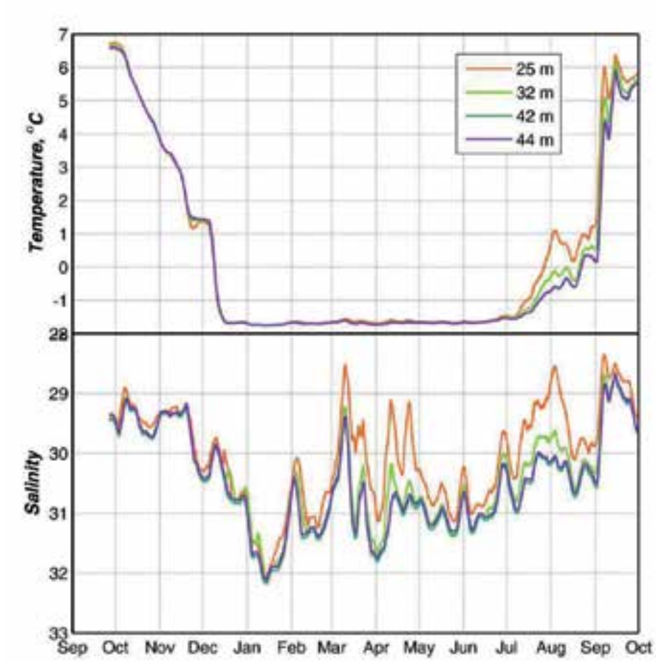

Figure 6. The one-year evolution of vertical thermohaline structure at NE02 mooring.

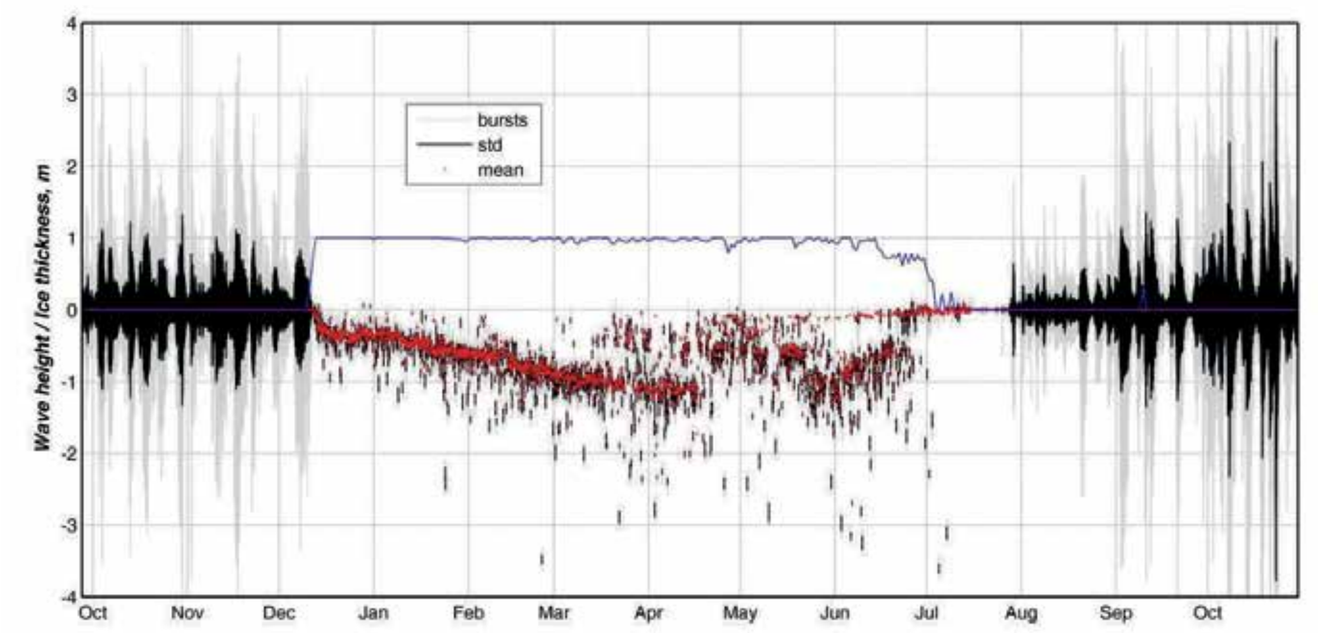

Figure 7. The sea-level heights and ice thicknesses recorded by upward-looking Nortek ADCP at AN01 mooring. Blue line shows AMSR-E sea-ice concentration in the mooring position.

Geophysical and electromagnetic parameters of the ice were measured, and general observations about the oil-contaminated ice were made. From the experimental measurements, the presence of crude oil appears to affect the temperature and bulk salinity profiles as well as the normalized radar cross section (NRCS) of the contaminated young sea ice. The measured temperature and bulk salinity profiles of the ice, as well as the crude oil distribution within the ice, were used to model the permittivity profile of the oil-contaminated ice by adapting two mixture models commonly used to describe sea ice to account for the presence of oil. Permittivity modeling results were used to simulate the NRCS of the oil-contaminated sea ice in an effort to determine the accuracy of the models. In addition, the application of X-ray microtomography in modeling the dielectric profile of oil-contaminated sea ice was examined. The sensitivity of the permittivity models for oil-contaminated sea ice to changes in temperature, frequency, and oil volume fraction was also examined.

DISCUSSION

Hemispheric-Scale Winter Drift Speeds and Changing Patterns of Arctic Sea Ice Motion: 1979-2015

Kaur et al. (2018) examined three interrelated research questions: i) what are the average large-scale drift patterns, and how do they vary in ii) space and iii) time, using trends and variability in hemispheric-scale sea ice drift for 36 winters within the period from 1979 to 2015 using the NSIDC sea ice drift product. In contrast to earlier studies, Empirical Orthogonal Functions (EOF) were used to statistically identify patterns in the ice drift field. Finally, changes relative to a boundary defined by a 36-year mean in ice drift were examined.

Kaur et al. (2018) found that the clear demarcation of these features indicates that the mean monthly winter dataset can be used to study these large-scale circulation regimes and their variability over time. The mean circulation pattern is in keeping with earlier studies while also illustrating a third ice drift feature in the Kara Sea.

In addition Kaur et al. (2018) found the following:

1. Long-term trend in the anomalies in the sea ice drift speeds from October 1979 to April 2015 show that drift speeds have increased across the entire Arctic basin and for all months of the winter period. Previous studies also observed the substantial increase the mean sea ice drift speeds for the winter season (+17% per decade). The overall positive trends in the sea ice drift speeds for winter have also been observed by Kwok et al. 2013, Spreen et al. 2011 and Hakkinen et al. 2008.
2. The basin-wide 36-year trend in the anomalies shows the strengthening of the BG, TPD and the drift patterns emerging from the Kara Sea. Statistically, positive drift trends are observed in all the three circulation patterns at the 95% confidence interval. An equally strong increasing trend is also observed for the ice drift along the western coast of Baffin Bay.

Evaluating Scattering Contributions to C-Band Radar Backscatter From Snow-Covered First-Year Sea Ice at the Winter–Spring Transition Through Measurement and Modeling

In this paper, Komarov et al. (2017) present model and measurement results for time-series angular dependencies of C-band nn and VV normalized radar cross-sections (NRCS) over first-year snow-covered sea ice during a winter-spring transition period. Experimental scatterometer and physical data were collected near Cambridge Bay, Nunavut, Canada, between May 20 and May 28, 2014, covering a severe storm event on May 25. They use the small perturbation scattering theory to model small-scale surface scattering, the Mie scattering theory to estimate the level of volume scattering in snow, and the Kirchhoff physical optics model to compute the large-scale surface scattering component. They observed good agreement between the model and experimental nn and VV NRCS. Before the storm, R^2 between model and experimental NRCS was 0.88 and 0.82 for VV and nn, respectively. After the storm, R^2 was 0.81 and 0.78 for VV and nn, respectively. Their model results suggest an overall increase in surface roughness after the storm event, supported by LiDAR measurements of the snow surface topography. Before the storm, the large-scale and small-scale surface scattering from the air-snow interface as well as volume scattering components dominated. After the storm, the large- and small-scale scattering contributions increased, while the volume scattering component considerably dropped. They attribute these effects to the increase in surface roughness and snow moisture content during the poststorm period. The results could aid in interpretation of timeseries synthetic aperture radar images with respect to physical properties of snow and ice during the winter-spring transition period.

Examining the Impact of a Crude Oil Spill on the Permittivity Profile and Normalized Radar Cross Section of Young Sea Ice

Neusitzer et al. (2018) look at the impact of crude oil on the permittivity of sea ice. An oil-in-sea ice mesocosm experiment was conducted at the University of Manitoba Sea-Ice Environmental Research Facility from January to March 2016 in which geophysical and electromagnetic parameters of the ice were measured, and general observations about the oil-contaminated ice were made. From the experimental measurements, the presence of crude oil appears to affect the temperature and bulk salinity profiles as well as the normalized radar cross section (NRCS) of the contaminated young sea ice. The measured temperature and bulk salinity profiles of the ice, as well as the crude oil distribution within the ice, were used to model the permittivity profile of the oil-contaminated ice by adapting two mixture models commonly used to describe sea ice to account for the presence of oil. Permittivity modeling results were used to simulate the NRCS of the oil-contaminated sea ice in an effort to determine the accuracy of the models. In addition, the application of X-ray microtomography in modeling the dielectric profile of oil-contaminated sea ice was examined. The sensitivity of the permittivity models for oil-contaminated sea ice to changes in temperature, frequency, and oil volume fraction was also examined. Figure 8 shows the results from for oil contaminated ice growth.

The performance of the permittivity models presented when subjected to changes in temperature, frequency, and oil volume fraction were evaluated and compared with that of an existing theoretical model. It was shown that the permittivity models were more sensitive to changes in ice temperature, and in some cases, more sensitive to changes in frequency and oil volume fraction than the existing linear model.

Freshwater-Marine Coupling in Hudson Bay

Led by Zou Zou Kuzyk as a collaborative project with Joel Heath and David Barber.

This project was successful through the winter 2015 -2017 programs. 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 successfully defended her thesis titled "Physical properties and isotopic characteristics of the winter water column

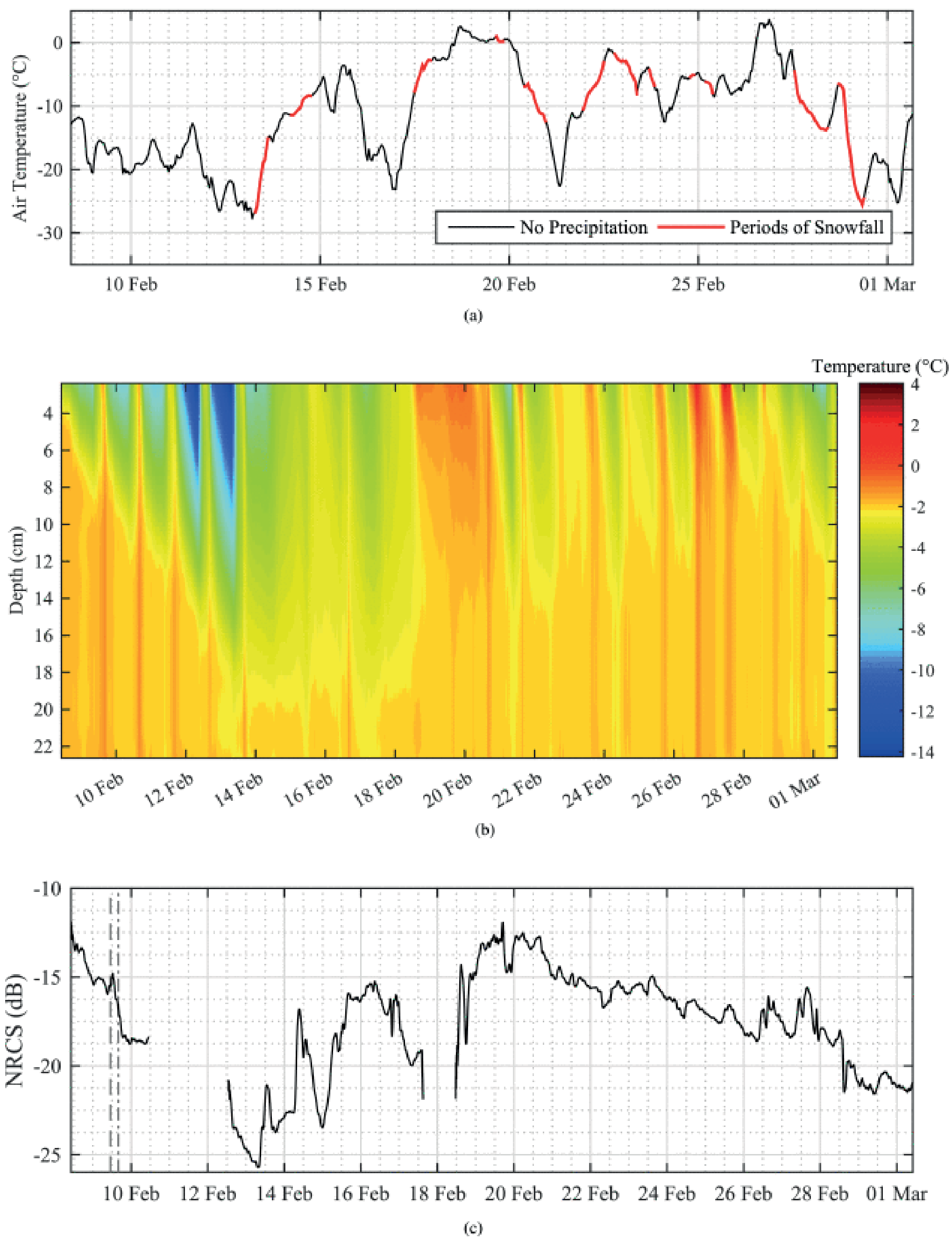

Figure 8. Data for the oil-contaminated ice growth period from February 8 to March 1, 2016. (a) Ambient air temperature in Winnipeg, MB, Canada (Environment Canada). (b) Measured ice/water column temperature profile. (c) Calibrated measured NRCS of oil-contaminated sea ice in the VV polarization at an incidence angle of 57°. Note that the dashed line indicates when oil-injection was performed, and the dashed-dotted line indicates when the evidence of the oil migrating up through the ice was first observed. The NRCS data from the afternoon of February 10 to the morning of February 12 were lost due to software issues with the scatterometer's data collection unit, and the data from the evening of February 17 to the morning of February 18 were lost due to a power-outage.

and landfast sea-ice surrounding the Belcher Islands, southeast Hudson Bay" in winter 2018.

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

CONCLUSION

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 researchers and organizations. We have reported on the successful contributions from to our objectives in previous reports, with a total of over 100 peer-reviewed publications since 2015. Below is a summary of the contributions from April 2017 to March 2018 to our overall objectives.

Macro-scale

- Kaur et al. (2018) looked at the large-scale sea ice motion regimes in the High Arctic.
- We've looked at the Arctic system at a more local to regional scale, examples include: Bendtsen et al. (2017); Boone et al. (2017), Barber et al. (2018); Andrews et al. (2017); Kirilov et al. (2017).

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: Hu et al. (2017), Pucko et al. (2017).
- Komarov et al. 2017 estimate the level of volume scattering in snow, and the Kirchhoff physical optics model to compute the large-scale surface scattering over first-year snow-covered sea ice.

Community-Based Monitoring (CBM)

- We helped support the community-based monitoring project in the Belcher Islands through MSc student Annie Eastwood. She successfully defended her thesis in winter 2018.
- Lauren Candlish and Zou Zou Kuzyk have continued to develop and the Hudson Bay IRIS and the Synthesis and Recommendations report. Through a collaborative writing workshop there have been recommendations to continue CMB programs and help develop new community-driven monitoring techniques.

Technology

- In contribution towards our technology objective we have developed mathematical models for remote sensing of sea ice (Komarov et al., 2017).
- Publications by Firoozy et al (2017, 2018) and Neusitzer (2017; 2018) used microwave remote sensing to detect changes in sea ice temperature and salinity when oil is injected into sea ice.
- Our group has also investigated microwave remote sensing of snow covered sea ice, including characteristics such as snow thickness, salinity distribution, melt ponds (Yackel et al. (2018; 2017); Beckers et al. (2017); Rickers et al (2017); Haas et al (2017)).

The number of peer-reviewed publications indicates the strong contributions to the scientific community. The importance of knowledge translation for these highly technical documents and making them available and accessible to communities, governments, and stakeholders is a continuing initiative. Our group has participated in community meetings, attended regional planning events, presented to school groups and presented at public lectures. We also have a strong working relationship with Manitoba Hydro, a major stakeholder in Hudson Bay, where we regularly meet with their executives to brief them on our scientific findings. In addition the IRISes are developed to take our scientific knowledge and present it in a meaningful and accessible format for stakeholders, communities and policy developers. Through the Sea Ice Project, we have written the climate chapter for IRIS-1 and we have lead the following chapters for IRIS-3: Atmosphere; Ocean; Sea Ice; Projections; Freshwater-Marine Interactions; and Transportation, in addition to contributing to several other chapters. The synthesis and recommendations report, which will be finalized shortly, summarizes the key points and gives recommendations directed to policy developers, researchers and government organizations. These IRIS documents will be a key legacy from ArcticNet and will be utilized by for future initiatives by stakeholders in the region.

ACKNOWLEDGEMENTS

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REFERENCES

Andrews, J., Babb, D., McKernan, M., Horton, B., & Barber, D. (2016). Climate Change in the Hudson Bay Complex: Opportunities and Vulnerabilities for the Port of Churchill's Marine Operations. University of Manitoba, Centre for Earth Observation Science.

Babb, D. G., Galley, R. J., Barber, D. G., & Rysgaard, S. (2016). Physical processes contributing to an ice free Beaufort Sea during September 2012. Journal of Geophysical Research: Oceans, 121(1), 267-283.

Barber, D. G., Hop, H., Mundy, C. J., Else, B., Dmitrenko, I. A., Tremblay, J. E., ... & Rysgaard, S. (2015). Selected physical, biological and biogeochemical implications of a rapidly changing Arctic Marginal Ice Zone. Progress in Oceanography, 139, 122-150.

Barber, D. G., McCullough, G., Babb, D., Komarov, A. S., Candlish, L. M., Lukovich, J. V., ... & Rysgaard, S. (2014). Climate change and ice hazards in the Beaufort Sea. Elem Sci Anth, 2.

Campbell, K., Mundy, C. J., Landy, J. C., Delaforge, A., Michel, C., & Rysgaard, S. (2016). Community dynamics of bottom-ice algae in Dease Strait of the Canadian Arctic. Progress in Oceanography, 149, 27-39.

Dmitrenko, I. A., Kirillov, S. A., Forest, A., Gratton, Y., Volkov, D. L., Williams, W. J., ... & Barber, D. G. (2016). Shelfbreak current over the Canadian Beaufort Sea continental slope: Wind-driven events in January 2005. Journal of Geophysical Research: Oceans, 121(4), 2447-2468.

Galley, R. J., Babb, D., Ogi, M., Else, B. G. T., Geilfus, N. X., Crabeck, O., ... & Rysgaard, S. (2016). Replacement of multiyear sea ice and changes in the open water season duration in the Beaufort Sea since 2004. Journal of Geophysical Research: Oceans, 121(3), 1806-1823.

Häkkinen, S., A. Proshutinsky, and I. Ashik (2008), Sea ice drift in the Arctic since the 1950s, Geophysical Research Letters, 35, L19704, doi:10.1029/2008GL034791.

Kwok, R., G. Spreen, and S. Pang (2013), Arctic sea ice circulation and drift speed: Decadal trends and ocean currents, Journal of Geophysical Research: Oceans, 118, 2408–2425, doi: 10.1002/jgrc.20191.

Lukovich, J. V., Hutchings, J. K., & Barber, D. G. (2015). On sea-ice dynamical regimes in the Arctic Ocean. Annals of Glaciology, 56(69), 323-331.

Ogi, M., Rysgaard, S., & Barber, D. G. (2016). Importance of combined winter and summer Arctic Oscillation (AO) on September sea ice extent. Environmental Research Letters, 11(3), 034019.

Spreen, G., R. Kwok, and D. Menemenlis (2011), Trends in Arctic sea ice drift and role of wind forcing: 1992–2009, Geophysical Research Letters, 38, L19501, doi: 10.1029/2011GL048970.

PUBLICATIONS

Andrews, J., Babb, D., Barber, D.G. (2017) "Climate change and sea ice: Shipping accessibility on the marine transportation corridor through Hudson Bay and Hudson Strait (1980–2014)". Elem Sci Anth. 2017;5:15. DOI: http://doi.org/10.1525/elementa.130.

Barber, D.G., W. Meier, S. Gerland, and C.J. Mundy (2017). Arctic Sea Ice. In: Snow, Water, Ice and Permafrost Assessment (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. ISBN-13 978-82-7971-101-8.

Beckers, J.F., J.A. Casey, C. Haas (2017), Retrievals of Lake Ice Thickness From Great Slave Lake and Great Bear Lake Using CryoSat-2, IEEE Transactions on Geoscience and Remote Sensing , PP(99), 1-13, doi: 10.1109/TGRS.2017.2677583.

Bendtsen, J., Mortensen, J., Lendert, K., Ehn, J., Boone, W., Galindo, V., Dmitrenko, I.A., Kirillov, S.A., Kjeldsen, K.K., Kristoffersen, Y., Barber, D., Rysgaard, S. (2017) "Sea ice breakup and marine melt of a retracting tidewater outlet glacier in northeast Greenland (81°N)". Scientific Reports, 7: 4941.

Boone W, Rysgaard S, Kirillov S, Dmitrenko I, Bendtsen J, Mortensen J, Meire L, Petrusevic V, Barber DG (2017) "Circulation and fjord-shelf exchange during the ice covered period in Young Sound-Tyrolerfjord, NE-Greenland (74°N)". Estuarine, Coastal and Shelf Science 194:205-216. http://dx.doi.org/10.1016/j.ecss.2017.06.021.

Dabboor, M., B. Montpetit, S. Howell, and C. Haas (2017), Improving Sea Ice Characterization in Dry Ice Winter Conditions Using Polarimetric Parameters from C- and L-Band SAR Data. Remote Sens., 9, 1270, doi:10.3390/rs9121270.

Dmitrenko, I.A., Kirillov, S.A., Rudels, B., Babb, D.G., Pedersen, L.T., Rysgaard, S., Kristoffersen, Y., and Barber, D.G. (2017) "Arctic Ocean outflow and glacier-ocean interactions modify water over the Wandel Sea shelf (northeastern Greenland)", Ocean Science, 13, 1045-1060, 10.5194/os-13-1045-2017.

Environment Canada. Historical Climate Data. Accessed: May 24, 2016. [Online]. Available: http://climate.weather.gc.ca/historical_data.

Firoozy, N., Neusitzer, T., Desmond, D., Tiede, T., Lemes, M., Landy, J., Stern, G., Mojabi, P., Rysgaard, S., Barber, D.G. (2017) "An electromagnetic detection case study on crude oil injections in a young sea ice environment", IEEE Transactions on Geoscience and Remote Sensing, 55(8): 4465-4475, doi: 10.1109/TGRS.2017.2692734.

Goldsmit, J., P. Archambault, G. Chust, E. Villarino, G. Liu, J. Lukovich, D.G. Barber, and K.L. Howland (2017). Projecting present and future habitat suitability of ship-mediated aquatic invasive species in the Canadian Arctic, Biological Invasions, doi:10.1007/s10530-017-1553-7.

Haas, C., J. Beckers, J. King, A. Silis, J. Stroeve, J. Wilkinson, B. Notenboom, A. Schweiger, S. Hendricks (2017), Ice and snow thickness variability and change in the high Arctic Ocean observed by in-situ measurements, Geophys. Res. Lett., 44, doi:10.1002/2017GL075434.

Hornby CA, Iacozza J, Hoover C, Barber DG, Loseto LL (2017) “Beluga whale *Delphinapterus leucas* late summer habitat use and support for foraging areas in the Canadian Beaufort Sea”. Mar Ecol Prog Ser 574:243-257. https://doi.org/10.3354/meps12178.

Howell, S. E., Komarov, A. S., Dabboor, M., Montpetit, B., Brady, M., Scharien, R. K., ... & Yackel, J. J. (2018). Comparing L-and C-band synthetic aperture radar estimates of sea ice motion over different ice regimes. Remote Sensing of Environment, 204, 380-391.

Hu, T.-B., Wang, F., Boone, W., Barber, D., Rysgaard, S. (2017) “Assessment and improvement of sea ice processing for dissolved inorganic carbon analysis”. Limnology and Oceanography Methods. doi: 10.1002/lom3.10229.

Kirillov, S., Dmitrenko, I., Rysgaard, S., Babb, D., Toudal Pedersen, L., Ehn, J., Bendtsen, J., and Barber, D. (2017) “Storm-induced water dynamics and thermohaline structure at the tidewater Flade Isblink Glacier outlet to the Wandel Sea (NE Greenland)”, Ocean Sci., 13(6), 947-959, https://doi.org/10.5194/os-13-947-2017, 2017. Published 22 Nov. 2017.

Komarov, A.S., Landy, J.C., Komarov, S.A., and D. G. Barber, (2017) “Evaluating Scattering Contributions to C-Band Radar Backscatter From Snow-Covered First-Year Sea Ice at the Winter–Spring Transition Through Measurement and Modeling”, IEEE Transactions on Geoscience and Remote Sensing, 55(10), pp. 5702-5718, Oct. 2017. doi: 10.1109/TGRS.2017.2712519.

Landy, J.C., Ehn. J.K., Babb, D., Theriault, N., and David G. Barber (2017). “Sea ice thickness in the Eastern Canadian Arctic: Hudson Bay Complex & Baffin Bay”. Remote Sensing of Environment, 200, 281-294, 2017 https://doi.org/10.1016/j.rse.2017.08.019.

Lange, B.A., H. Flores, C. Michel, J.F. Beckers, A. Bublitz, J.A. Casey, G. Castellani, I. Hatam, A. Reppchen, S.A. Rudolph, and C. Haas (2017), Pan-Arctic sea ice-algal chl a biomass and suitable habitat are largely underestimated for multi-year ice. Glob Change Biol. 2017;00:1–17. https://doi.org/10.1111/gcb.13742.

Lukovich, J. V., Geiger, C. A., and Barber, D. G. (2017) “Method to characterize directional changes in Arctic sea ice drift and associated deformation due to synoptic atmospheric variations using Lagrangian dispersion statistics”, The Cryosphere, 11, 1707-1731, https://doi.org/10.5194/tc-11-1707-2017, 2017. Published: 24 Jul 2017.

Mahmud, M., Geldsetzer, T., Nandan, V., Howell, Stephen., Yacjel, J., Ramjan, S. (2017). Incidence Angle dependency of L-band Microwave backscatter of Arctic Sea Ice, Proceedings of Earth Observation Summit 2017.

Nandan, V., Geldsetzer, T., Mahmud, M., Yackel, J., & Ramjan, S. (2017). Ku-, X-and C-Band Microwave Backscatter Indices from Saline Snow Covers on Arctic First-Year Sea Ice. Remote Sensing, 9(7), 757.

Nandan, V., Geldsetzer, T., Mahmud, M., Yackel, J., Fuller, M., Gill, JPS., Ramjan, S. (2017). Multi-frequency microwave backscatter indices from saline snow covers on smooth first-year sea ice, Proceedings of IGARSS 2017, 346-349.

Nandan, V., Geldsetzer, T., Mahmud, M., Yackel, J., Scharien, R., Ramjan, S. (2017). Saline Snow covers on First-Year Sea Ice (FYI) – Friend or Foe for CryoSat-2 derived FYI Thickness Estimates? Proceedings of Earth Observation Summit 2017.

Nandan, V., Geldsetzer, T., Yackel, J. J., Islam, T., Gill, J. P., & Mahmud, M. (2017). Multifrequency Microwave Backscatter From a Highly Saline Snow Cover on Smooth First-Year Sea Ice: First-Order Theoretical Modeling. IEEE Transactions on Geoscience and Remote Sensing, 55(4), 2177-2190.

Nandan, V., Geldsetzer, T., Yackel, J., Mahmud, M., Scharien, R., Howell, S., ... & Else, B. (2017). Effect of Snow Salinity on CryoSat-2 Arctic First-Year Sea Ice Freeboard Measurements. Geophysical Research Letters, 44(20).

Nandan, V., Scharien, R., Geldsetzer, T., Mahmud, M., Yackel, J. J., Islam, T., ... & Duguay, C. (2017). Geophysical and atmospheric controls on Ku-, X-and

C-band backscatter evolution from a saline snow cover on first-year sea ice from late-winter to pre-early melt. Remote Sensing of Environment, 198, 425-441.

Nandan, V., Scharien, R., Geldsetzer, T., Mahmud, M., Yackel, J., Ramjan, S. (2017). Ku-, X-, and C-band Backscatter Evolution from a Saline Snow Cover on First-Year Sea Ice from Late-Winter to Pre-Early Melt. Proceedings of Earth Observation Summit 2017.

Nasonova, S., R.K. Scharien, C. Haas, and S.E.L. Howell (2017), Linking Regional Winter Sea Ice Thickness and Surface Roughness to Spring Melt Pond Fraction on Landfast Arctic Sea Ice. Remote Sens., 10, 37, doi:10.3390/rs10010037.

Neusitzer, T.D., Firoozy, N., Tiede, T.M., Desmond, D.S., Lemes, M.J.L., Stern, G.A., Rysgaard, S., Mojabi, P., and D.G. Barber (2018) Examining the impact of a crude oil spill on the permittivity profile and normalized radar cross-section of young sea ice. IEEE Transactions on Geoscience and Remote Sensing. 56:921-936. DOI: 10.1109/TGRS.2017.2756843.

Neusitzer, T.D., Firoozy, N., Tiede, T.M., Desmond, D.S., Lemes, M.J.L., Stern, G.A., Rysgaard, S., Mojabi, P., Barber, D.G. (2017) "Examining the impact of a crude oil spill on the permittivity profile and normalized radar cross-section of young sea ice". IEEE Transactions on Geoscience and Remote Sensing. TGRS-2017-00492. DOI: 10.1109/TGRS.2017.2756843.

Pućko, M., Stern, G.A., Burt, A., Jantunen, L.M., Bidleman, T.F., Macdonald, R.W., Barber, D.G., Geilfus, N.-X., Rysgaard, S. (2017) "Current Use Pesticide (CUP) and legacy Organochlorine Pesticide

dynamics at the Ocean-Sea-ice-Atmosphere interface in Resolute Passage, Canadian Arctic, during winter-summer transition". Science of the Total Environment, 580:1460-1469, doi: 10.1016/j.scitotenv.2016.12.122.

Ramjan, S., Geldsetzer, T., Yackel, J., Scharien, R., Nandan, V., Mahmud, M. (2017). An Integrated Approach Utilizing RADARSAT-2 SAR and GLCM Texture to Quantify the Relationship between Aerial Melt-Pond Distribution and Microwave Backscatter. Proceedings of Earth Observation Summit 2017.

Ricker, R., S. Hendricks, L. Kaleschke, X. Tian-Kunze, J. King, and C. Haas (2017), A Weekly Arctic Sea-Ice Thickness Data Record from merged CryoSat-2 and SMOS Satellite Data. The Cryosphere, 11, 1607–1623, doi: 10.5194/tc-11-1607-2017

Scharien, R. K., Segal, R., Nasonova, S., Nandan, V., Howell, S. E. L. & Haas, C. (2017). Winter Sentinel-1 backscatter as a predictor of spring Arctic sea ice melt pond fraction. Geophysical Research Letters, 44. https://doi.org/10.1002/2017GL075547.

Scharien, R. K., Segal, R., Yackel, J. J., Howell, S. E. L., & Nasonova, S. (2017). Linking winter and spring thermodynamic sea-ice states at critical scales using an object-based image analysis of Sentinel-1. Annals of Glaciology, 1-15.

Szanyi, S., Lukovich, J.V., and Barber, D.G. (2017). "Lagrangian analysis of sea-ice dynamics in the Arctic Ocean", Polar Research, 35(1), 30778, 10.3402/polar.v35.30778.

Yackel, J. J., Gill, J. P., Geldsetzer, T., Fuller, M. C., & Nandan, V. (2017). Diurnal Scale Controls on C-Band Microwave Backscatter From Snow-Covered First-Year Sea Ice During the Transition From Late Winter to Early Melt. IEEE Transactions on Geoscience and Remote Sensing.

Yackel, J. J., Nandan, V., Mahmud, M., Scharien, R., Kang, J. W., & Geldsetzer, T. (2018). A spectral mixture analysis approach to quantify Arctic first-year sea ice melt pond fraction using QuickBird and MODIS reflectance data. Remote Sensing of Environment, 204, 704-716.

Zhao, J.P., D.G. Barber, S.G. Zhang, Q.H. Yang, X.Y. Wang, and H.J. Xie (2018). Record low sea-ice concentration in the central Arctic during summer 2010, Adv. Atmos. Sci., 35, doi: 10.1007/s00376-017-7066-6.

Zheng, J., Geldsetzer, T., & Yackel, J. (2017). Snow thickness estimation on first-year sea ice using microwave and optical remote sensing with melt modelling. Remote Sensing of Environment, 199, 321-332.

Zheng, J. (2017). Snow Thickness Estimation on First-Year Sea Ice from Microwave and Optical Remote Sensing and Melt Modelling. A thesis submitted to the Faculty of Graduate Studies at the University of Calgary.

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

Project Team

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ABSTRACT

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 to identify local species from only a few liters of water, however it has mainly been used in freshwater systems in the south. This project therefore aims 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, this project aims to adapt and calibrate the eDNA method for Arctic organisms and monitor Arctic biodiversity in sensitive Arctic areas (i.e. commercial ports). It is the perfect time for integrating molecular monitoring methods for Arctic ecosystems in regards to biotechnology accessibility, biotechnology advances, actual knowledge of marine biodiversity and the access to pristine environments (i.e., before biodiversity shifts have occurred).

KEY MESSAGES

- An innovative biodiversity monitoring tool, the eDNA method, was successfully used to detect Arctic coastal species and potential introduced nonindigenous species (NIS).
- A library of Arctic DNA sequences is now available. This may now be used to evaluate and quantify shifts in the Arctic marine biodiversity in sensitive coastal areas, such as Churchill, Iqaluit, Deception Bay, Pond Inlet and Milne Inlet.
- Our results demonstrate that the analysis of eDNA from Arctic water samples could increase the power of detection, spatial coverage and frequency of sampling, thus improving detection of biodiversity shifts in large coastal Arctic ecosystems. Local variability of marine metazoan eDNA in the Arctic has been characterized. Results showed that species composition is vertically heterogeneous, in part due to eDNA river inflow in the estuarine ecosystem, and differed between water column and tide pools. Vertical eDNA distribution is also significantly altered across tides and seasons; sustaining that temporal scales need to be considered to standardize the eDNA method. eDNA monitoring surveillance is also improved when sampling under-ice cover; eDNA could thus expand the time window to survey coastal biodiversity in the Arctic.
- We have extended this eDNA water column project to testing eDNA also collected in sediments samples to evaluate if marine sediments have greater magnitude of eDNA concentration than seawater or result in detection of different species. We thus provide the first Arctic eDNA species list collected in sediments and show that eDNA in sediment increase species richness record when added to eDNA collected in water.
- In collaboration with McGill University (Dr. Melania Cristescu), we showed that biodiversity monitoring was more efficient using eDNA metabarcoding than bulk zooplankton metabarcoding. In marine ecosystem, the origin of eDNA is 57% from zooplankton degradation vs. ~43% from the release of tissue or mucus from adults/recruits species, whereas this proportion varies with water river discharge in estuarine ecosystem due to freshwater eDNA transport from upstream.
- This project has provided a basis for establishment of the very first NIS monitoring program in the Canadian Arctic via the development of community based monitoring (CBM) network/ capacity composed through training local indigenous community members and northern research staff.
- We developed many partnerships to perform large-scale eDNA monitoring throughout many sensitive Arctic ecosystems. These include: 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), Polar Continental Shelf Program, the Nunavut Wildlife Management Board and the Nunavik Marine Region Wildlife Board.
- Taken together, all of our results from the last four years and our international collaboration Coastal SEES Collaborative Research Network (NSF funding) highlight the potential of eDNA metabarcoding to facilitate aquatic biodiversity surveys worldwide, to predict Arctic invasion risk (i.e. port connectivity in ports) and allow the development of a list of recommendations for port eDNA metabarcode surveys.

RESEARCH OBJECTIVES

We reached the objectives identified initially in 2014, at the start of our ArcticNet Phase IV project as requested and largely extended the scope of this study project through multiple additional funds. The following list of objectives comprises those of the last three years.

1. Surveillance of Coastal Arctic Biodiversity by optimizing the effectiveness of eDNA Sequencing used for capturing the broadest metazoan Arctic biodiversity from water samples.
   - 1.1. Using the four primers tested for this objective (two mitochondrial COI primer pairs and two nuclear 18S primer pairs) we compiled a species list reference database of Arctic species and potential aquatic invasive species (AIS)/nonindigenous species (NIS).
   - 1.2. We built a library of Arctic DNA sequences; which will provide a baseline for evaluating Arctic coastal biodiversity shifts.
2. Detecting Marine Biodiversity Shifts in ports with substantial shipping activity by:
   - 2.1. Optimizing water sampling strategies for eDNA in Arctic marine environments by using the primers developed in objective 1.
   - » We showed in previous years that eDNA is spatially and temporally heterogeneous within harbors.
   - » We evaluated tide and annual eDNA variation to standardize the water sampling.
   - » Because the efficiency of the eDNA monitoring surveillance is improved when sampling under-ice cover, we evaluated the eDNA variation during the ice formation.
   - » We contrasted eDNA marine sediments to eDNA seawater to evaluate eDNA vertical deposition (i.e. vertical transport) and improve species performance.
   - 2.2. 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. Large scale biodiversity monitoring is essential to the elaboration of global predictive NIS models and to inform international policy makers about Arctic coastal invasion risk. The eDNA standardized approach could be an appropriate tool to manage AIS invasions. We improved the potential for use of environmental DNA (eDNA) to provide an easier and taxonomically broader survey method for metazoans (multicellular animals) in commercial ports across the world by:
   - 3.1. The standardization of the utilization of two published primer sets, the mitochondrial COI gene and the nuclear 18S gene, that amplify different sequences across a wide-range of metazoans (multi-cellular animals) at the global scale (i.e. also on potential Canadian Arctic invaders detected in international ports).
   - 3.2. Examining variation in eDNA sampling and sequencing effort at different spatial scales from these datasets in various environmental conditions.
   - 3.3. Testing two approaches to estimate global biodiversity patterns (1) the data to the lowest observed read or sample number, or (2) use of biodiversity metrics that are robust to unequal sampling efforts.
4. Establishment of a community based monitoring (CBM) network/capacity by:
   - 4.1. Providing training to local community members and northern research staff in user-friendly port survey collection methods and eDNA sampling techniques.

KNOWLEDGE MOBILIZATION

- Ikaarvik northern community youth training workshops. Linking Science and Community Knowledge in the Arctic; Pond Inlet (August 2017) and Salluit (January 2018).
- Oral presentations at the Arctic Change (Québec City, December 2017).
- Oral presentation at the 7th International Barcode of Life Conference (South Africa, November 2017).
- Oral presentation at the ICES Working Group. Introductions and Transfers of Marine Organisms (WGITMO), WHOI (USA: March 2017).
- 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).
- Globe and Mail article, September 2017: Invaders in the Arctic: How ships and climate change are bringing strange species to Nunavut.
- C3 Expedition Facebook Live interview on invasive species in the Arctic (September 2017).
- CBC (Découverte : April 2018; 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, August 2017 and January 2018).
- 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, April and November 2017).
- Ikaarvik one 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).
- Salluit radio station - presentation and question and answer period across 14 Nunavik communities (March 2017).

INTRODUCTION

Over the past century, aquatic invasive species (AIS) have become a serious threat to global biodiversity [1, 2]. Shipping (ballast and hull fouling) has been one of the major vectors for transport of AIS many of which are coastal or estuarine in origin. Although most introductions have occurred at southerly latitudes where there is greater shipping activity, climate change, resource exploitation and the resulting increase in Arctic shipping activity are expected to increase the risk of new introductions to Arctic waters [3-5]. Canada has the longest coastline in the world and the majority of it is located in Arctic waters, this region is at high risk of invasion. Early detection monitoring systems, coupled with mechanisms for rapid response increase the likelihood of identifying invasions at early stages when there is a greater chance of developing environmentally and economically efficient solutions for elimination or containment, or for preparing to adapt to the presence of a new species in the ecosystem. New and emerging techniques such as the analysis of environmental DNA from water or sediments (eDNA or DNA from cells of organisms shed into the environment) have great potential as relatively cost-effective, user-friendly tools for detecting the presence of new species and tracking shifts in biodiversity over time [6].

The analysis of environmental DNA (eDNA) could be a revolutionary tool for overcoming the lack of extensive species distribution data. The eDNA method allows the detection of traces of DNA from macro-organisms in cellular or extracellular form in water [7]. 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 [8-11]. 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 [6, 12]. 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 [13]. 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

Goal 1. Optimize the effectiveness of the eDNA sequencing approach

- We calculated the proportion of Arctic species that have been sequenced (i.e. an estimation of the unknown Arctic costal biodiversity).
- A bioinformatics pipeline, Barque, has been developed and optimized for the COI and the 18S region to determine the sequences at the phylum, genus and species level.
- The Barque bioinformatics pipeline is freely available on the Github long-term software hosting site (www.github.com/enormandeau/barque).
- The proportion of missing species assignments due to BOLD incompleteness was further explored for each metazoan phyla using Operational Taxonomic Units (OTU) clustering according to 97% similarity with swarm 2.2.0 [14]. OTUs represented by a single read (singletons) were excluded and the identity between the representative sequences and the BOLD database was done using vsearch [15]. For each phyla, proportion of the biodiversity assigned to the species level was obtained from the number of OTUs between 97–100% (similar to threshold used to assign species for sequences in the BOLD database) relative to those between 80–97% (i.e. below species level).
- We evaluated the performance of the sampling effort and the depth of sequencing (i.e. accumulation curves according to number of eDNA sequences and the number of sample).

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, amplified, sequenced and analyzed.
- Species databases pooled to evaluate the eDNA efficacy compared to local knowledge.
- Data analyzed for location comparison (i.e. depth and tide pools).
- 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 dDNA efficiency between different marine invertebrate taxa.

Temporal variation

- Annual in Churchill (summer 2015-2016-2017).
- Tidal variability in Churchill and Milne Inlet (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 (September to December 2017) and Pond Inlet (August to November 2017); 20 samples each survey.
- All samples extracted, amplified and sequenced.
- Data analyzed for the seasonal variation for Iqaluit (cf. last-year report) and for the tidal effect for Churchill and Milne Inlet.

Water vs sediment eDNA

Because use of sediments may significantly increase biomonitoring from eDNA in coastal ecosystems, we also collected eDNA from sediment samples (sedDNA).

- 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 electrophores and Illumina MiSeq sequencing have been completed.
- All samples extracted, amplified and sequenced.
- Species listed developed.

Bulk plankton metabarcoding

To improve port survey and standardize sampling to assess biodiversity and detect invasive species from coastal marine environments in the Arctic, we compared efficacy of metabarcoding with various sampling methods (bulk plankton collections and eDNA in water) across varying spatial and temporal gradients.

- Conducted vertical tows with the 80 um 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).
- Churchill and Iqaluit samples are extracted, amplified and Illumina MiSeq sequenced. Deception Bay samples are extracted and amplified and will be sequenced in the next month (collaboration with McGill University).
- Data analyzed for Churchill and Iqaluit.

Protocols are similar to the last year's report

- Sampling: the efficiency of various eDNA water sampling methods has been compared.
- Preservation: the Longmire's lysis/preservation buffer has been shown to have good efficacy for

shipping samples at room temperature (up to ~1 month).

- Extraction: a faster and cheaper DNA extraction method has also been developed using QIAshredder and phenol chloroform protocol.
- Amplification: To reduce cross-contamination risk, DNA amplifications were performed in a one-step dual-indexed PCR approach specifically designed for Illumina instruments by the "Plate-forme d'Analyses Génomiques" (IBIS, Université Laval).

Goal 3. Community based monitoring network

This project has built strong working relationships between DFO and university researchers and northern communities. It engages youth and other community members in AIS research, ensuring research questions, location and timing of data collection are of maximum relevance to these communities, and local Traditional Knowledge is fully incorporated. The project also builds capacity within these communities for youth to play leadership roles in bridging research and their communities' interests. Basic port survey collection methods and eDNA sampling techniques was conducted annually in summers 2015, 2016 and 2017 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, Milne Inlet 2017).
- Local boats and guides hired in each community (Churchill 2015-2016, Iqaluit 2015-2016, Salluit-Deception Bay 2016, Milne Inlet 2017).
- 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 and Salluit as well as with HTO members in four communities (2015-2018). Both communities are in the vicinity of, and have an interest in, nearby mining activities which rely on shipping as the main mode of transport for cargo and resources.
- 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 (Salluit, Kangiqsujuaq, Kuujuak, Igloolik, Hall Beach, Iqaluit, Pond Inlet; 2015-2017).
- eDNA training workshops conducted with Nunavut Arctic College students in two communities (Iqaluit and Pond Inlet November 2015).

Goal 4. Estimating global biodiversity patterns with eDNA metabarcoding

Differences in sampling methods and effort must be considered when interpreting results from these surveys. Here we conducted an eDNA metabarcoding survey in four commercial ports across the world, which are hotspots for aquatic biological invasions, to understand the influence of sampling methods on biodiversity patterns and nonindigenous species detection. International ports were 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 2 sites on July 11th, 2014 from docks (n=20 per site). In Adelaide, a total of 66 samples were taken across 7 sites on July 3rd, 2014 from a boat, with 4 sites sampled within 2 meters of a dock and 3 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.
- Explored how sampling method and effort influenced biodiversity patterns and nonindigenous species detection.
- Compared two common approaches for comparing biodiversity metrics: 1) rarefied the data to the lowest effort, or 2) used non-parametric estimates of biodiversity that are robust to unequal sampling efforts.

RESULTS

Considering our excellent progress in development of eDNA methodology for assessing Arctic marine biodiversity over the past three years, this technical goal has been achieved and the results presented in this report demonstrate the quality of our protocol. In addition to develop and calibrate the eDNA metabarcoding to monitor Arctic species, major topics of research during 2017-2018 were to develop an understanding of patterns with respect to spatial and temporal variation, study the source of eDNA, compare eDNA water and sediment. These results will help to monitor and manage potential AIS (aquatic invasive species) invasions in Arctic ports.

Goal 1

DNA sequences of ~50% of known Canadian Arctic species and potential invaders are currently present in public databases. A similar proportion of operational taxonomic units was identified at the species level with eDNA metabarcoding, for a total of 181 species identified at both sites. Results show that sampling and sequencing efforts have been sufficient (i.e. accumulation curves reaching the asymptotes; Figure 1 and 2). It is noteworthy that the comparison

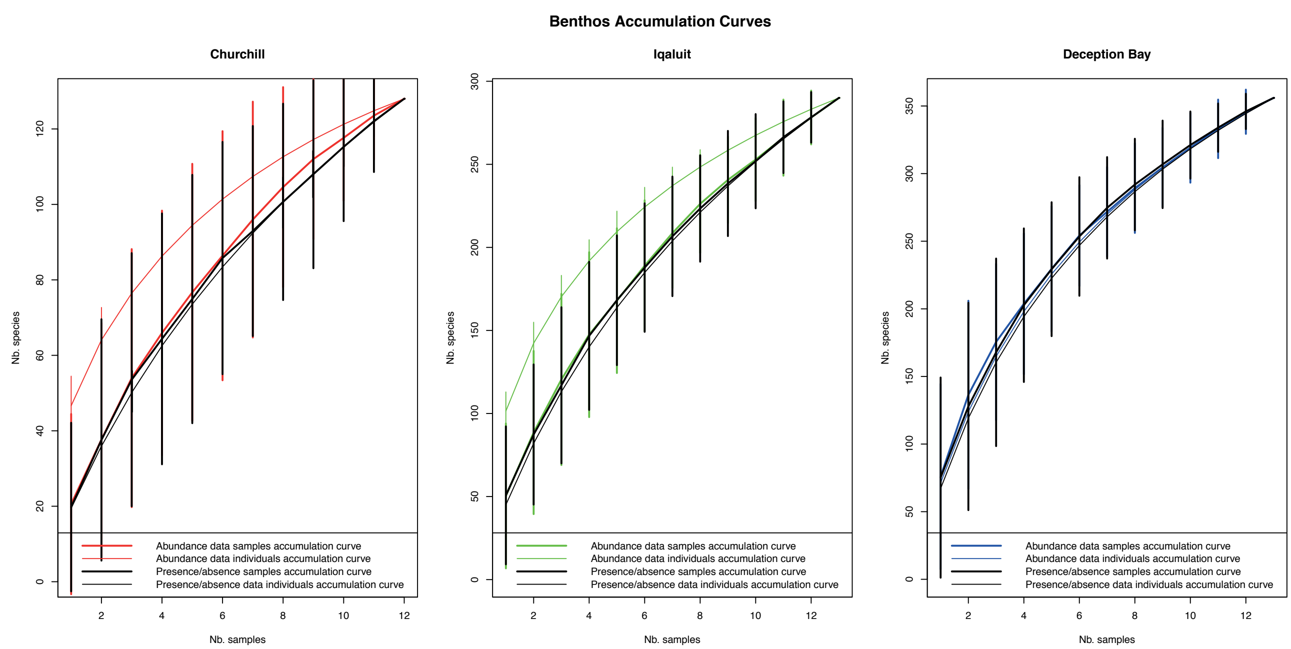

Figure 1. Accumulation curves of eDNA benthos in the spatial variation context for Churchill, Iqaluit and Deception Bay harbours. Solid bold line denotes the sample accumulation while the light line denotes the reads accumulation. Errors bars represent 95% confidence intervals.

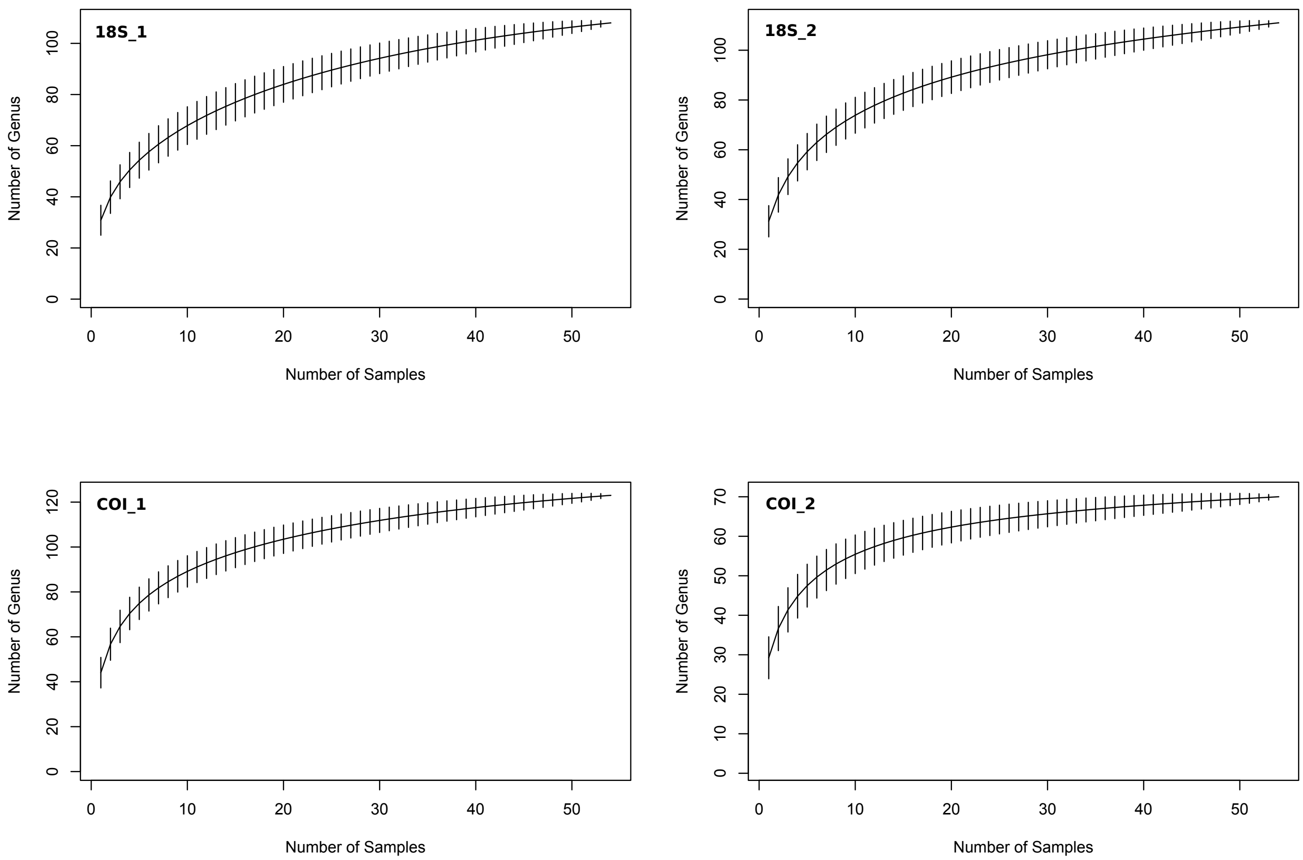

Figure 2. Accumulation curves of eDNA marine metazoans for Churchill harbor tide variation (temporal variation context) with the four primers used in this analysis. In this figure, only the accumulation curves were represented. Errors bars represent 95% confidence intervals.

of the primers highlighted the presence of different major phyla (Figure 5 and 9). In the Figure 5, the 18S primers are dominated by Annelida, Bryozoa, Hydrozoa and Mollusca whereas the COI primers are dominated by Annelida, Arthropoda, Chordata, Mollusca and Porifera.

Goal 2

In addition, to provide evidence that eDNA may be used to assess Arctic biodiversity (goal 1), we show that standardized eDNA approaches developed to evaluate Arctic coastal biodiversity will need to consider local spatio-temporal variation.

Spatial variation

The species-specific approach of the eDNA method and the relative effect of the local environmental conditions (biotic and abiotic factors) are supported by the strong eDNA community structure observed among harbours (Figure 3). Within ports, despite the cold and well-mixed coastal environment, species composition was vertically heterogeneous, in part due to eDNA river inflow in the estuarine ecosystem, and differed between water column and tide pools. Among intra-port samples, the Beta diversity was lower for eDNA than traditional sampling methods (i.e. benthic trawl, van veen grab sampler and nets (oblique and vertical); Figure 4), supporting that the eDNA dispersion in the environment may lead to a more broad-scale integrated

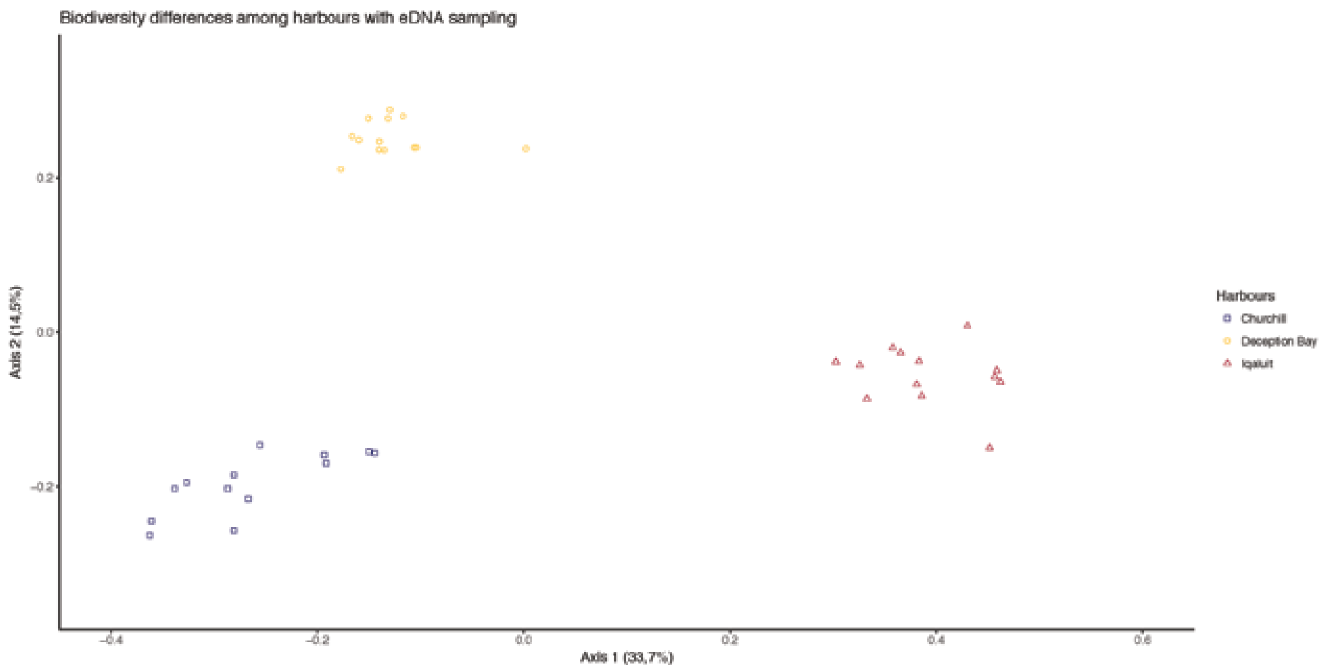

Figure 3. Principal coordinate analyses (PCoA) of eDNA marine biodiversity differences among Churchill, Iqaluit and Deception Bay harbours. This PCoA is based on the Sorensen index (incidence based), with each point representing a particular station from each port.

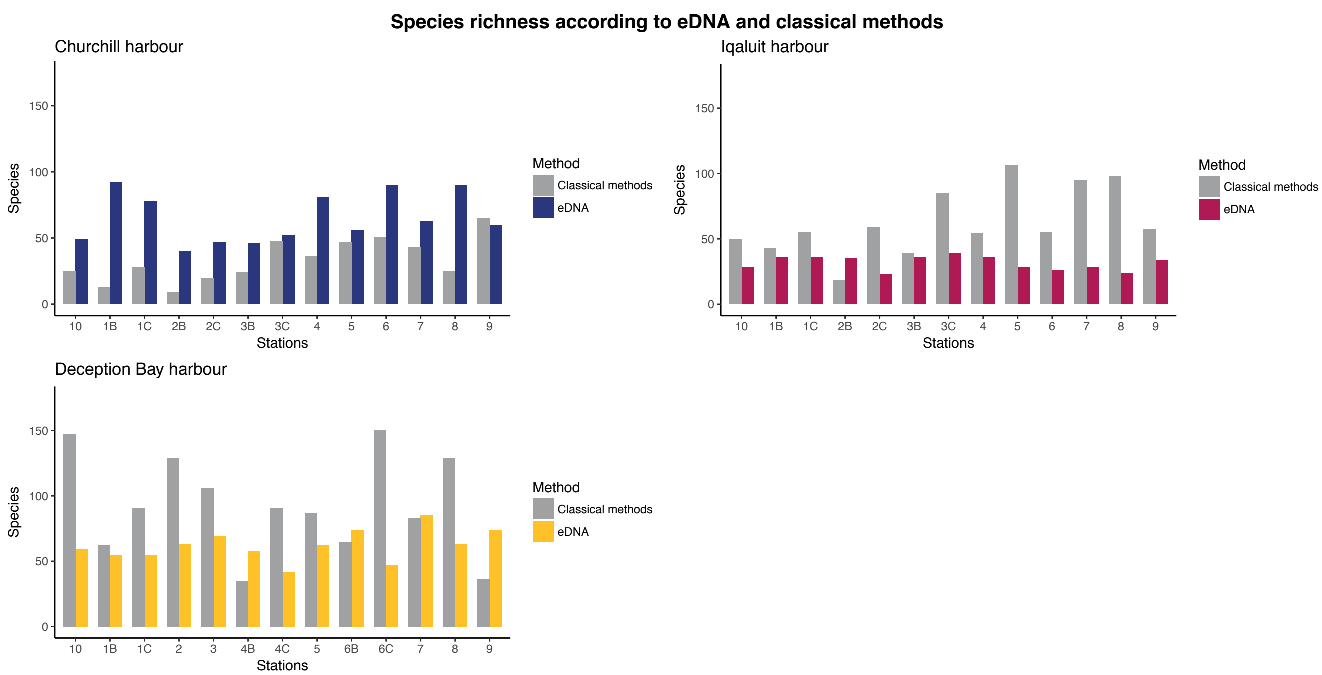

Figure 4. eDNA Species richness vs. classical methods Species richness. The species richness was represented for each station sampled among Churchill, Iqaluit and Deception Bay harbours.

Table 1. Mean and standard deviation (SD) of the species richness.

Harbours / mean of Species richness	eDNA	Classical methods
Churchill	64,92 ± 18,07	33,38 ± 15,82
Iqaluit	31,46 ± 5,20	62,61 ± 24,82
Deception Bay	62,00 ± 11,14	93,15 ± 36,61

biodiversity index than biodiversity obtained using traditional sampling methods (Table 1).

Temporal variation

Detecting loss or gain of biodiversity using eDNA requires knowledge about eDNA temporal variation to compare samples. Previous results (see above) showed a strong vertical eDNA distribution in estuarine ecosystem due to the river outcome. Here we further show the strong tide effect across phyla detection (Figure 5). Although the same phyla are present for the three tide conditions, the relative abundance is systematically different. However, further research

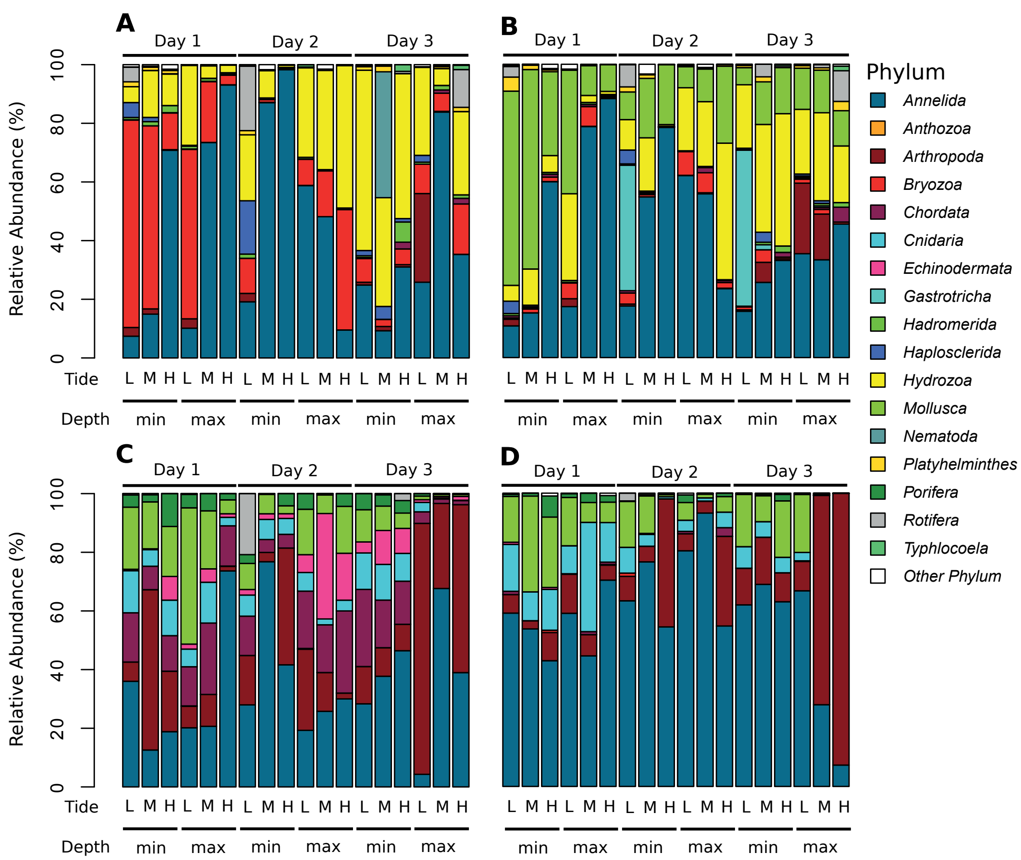

Figure 5. eDNA taxonomic composition at the phylum level for the Churchill harbor tide variation. This figure was performed separately with four primers: A: F-574- R-952 (18S1), B: TAReuk454FWD1- TAReukREV3 (18S2), C: mlCOIintF-jgHCO2198 (COI1), D: LCO1490-ill_C_R (COI2). The sampling took place for three days. L: low tide, M: middle tide (between low and high tide), H: high tide. Two different depths were performed. Min: surface, max: deep (~50 cm from the bottom).

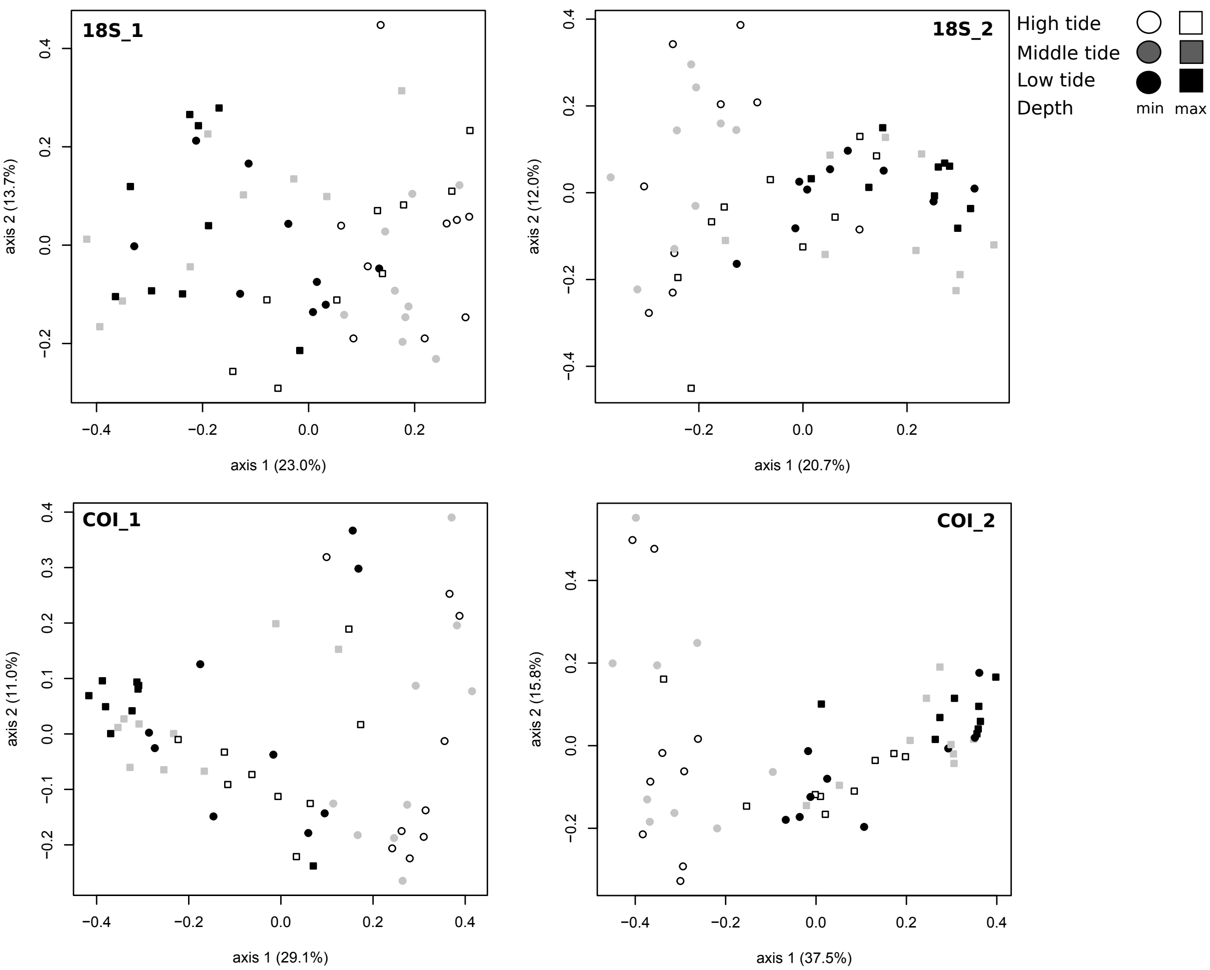

Figure 6. Principal coordinate analyses (PCoA) of eDNA marine metazoans for Churchill harbor tide variation with the four primers used in this analysis. This figure was performed separately with the four primers (see legend Figure 5). The sampling took place for three days. Low tide, middle tide (between low and high tide) and high tide are represented by the color black, grey and white respectively. Two different depths were performed: surface depths represented by the circle point and the deep depths (~50 cm from the bottom) represented by the square point.

is needed to elucidate factors driving the strong variability observed among days.

Although the analyses reveal partially overlapping clusters corresponding to the groups of tide, they are nevertheless distinct (Figure 6). The middle tide group showed the most spread, suggesting an intermediary state between low and high tides. This pattern is consistent among the four primer pairs, underlining the strong tide effect (PERMANOVA tests for each primer: $P < 0.0001$; see Table 2). Moreover, the two different depths also cluster according the group of tides and are significative different (Table 2). More precisely, the day effect, the tide effect and the depth effect are significate for each primer. Although the marine community is influence by temporal variation, the marine biodiversity has a specific tide structure/

Table 2. Summary of PERMANOVA test statistics of eDNA marine metazoans for Churchill harbor tide variation with the four primers (COI1, COI2, 18S1 and 18S2; (see legend Figure 5).

Primer	Source of variation	PERMANOVA		
		F-Value	R2	Pr(>F)
18S 1	Day	9.667	0.130	<0.001***
	Tide	2.425	0.065	<0.001***
	Depth	4.526	0.061	<0.001***
	Day*Tide	2.309	0.062	0.001 **
	Day*Depth	3.042	0.041	<0.001***
	Tide*Depth	1.660	0.045	0.024*
	Day*Tide*Depth	1.660	0.031	0.246
18S 2	Day	7.374	0.099	<0.001***
	Tide	2.459	0.066	<0.001***
	Depth	5.215	0.070	<0.001***
	Day*Tide	2.278	0.061	<0.001***
	Day*Depth	3.159	0.043	<0.001***
	Tide*Depth	2.046	0.055	0.002**
	Day*Tide*Depth	1.406	0.038	0.076
COI 1	Day	3.208	0.046	<0.001***
	Tide	2.793	0.080	<0.001***
	Depth	6.637	0.095	<0.001***
	Day*Tide	1.592	0.046	0.028*
	Day*Depth	3.281	0.047	<0.001***
	Tide*Depth	1.631	0.047	0.025*
	Day*Tide*Depth	1.189	0.034	0.198
COI 2	Day	2.930	0.041	0.002**
	Tide	2.949	0.083	<0.001***
	Depth	7.175	0.101	<0.001***
	Day*Tide	1.877	0.053	0.014*
	Day*Depth	2.456	0.034	0.010*
	Tide*Depth	2.577	0.072	<0.001***
	Day*Tide*Depth	0.946	0.026	0.508

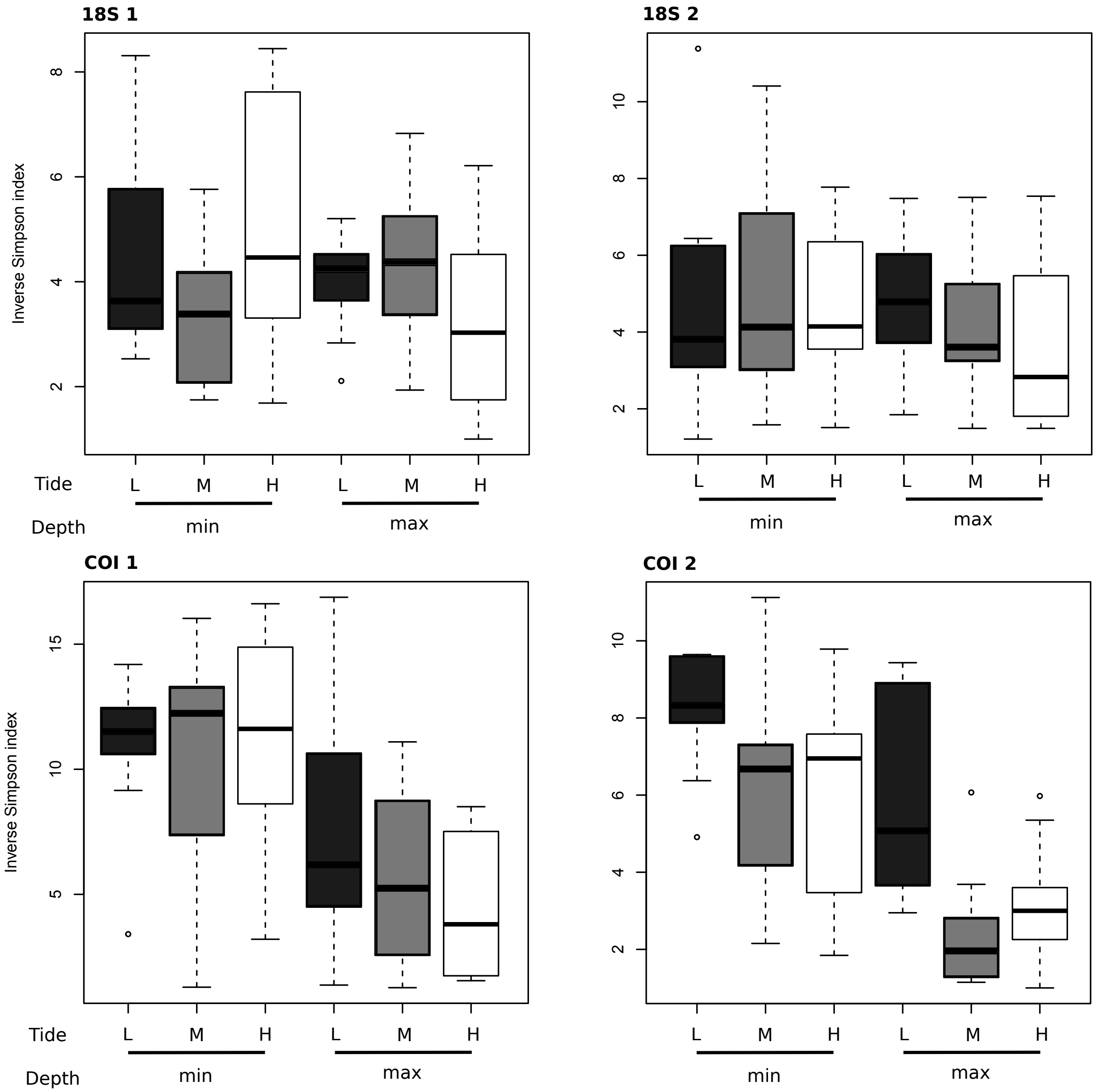

Figure 7. Box plot on alpha diversity of eDNA marine metazoans for Churchill harbor tide variation with the four primers used in this analysis. This analysis was performed with the inverse Simpson's index. This figure was generated separately with the four primers (see legend Figure 5). The sampling took place during incoming tide for three days. L: low tide, M: middle tide (between low and high tide), H: high tide. Two different depths were performed. Min: surface, max: deep (~50 cm from the bottom).

composition. However, no pattern is found at the alpha diversity level for the four primers (Figure 7). There is no difference between the two depths among the tide groups. Thus, the inverse Simpson index is not significant (Table 3). Similar results are also obtained using the Shannon index.

Table 3. Summary of GLM and ANOVA test statistics on the alpha diversity (inverse of Simpson index) of eDNA marine metazoans for Churchill harbor tide variation with the four primers used in this analysis.

Primers	Effect	GLM + ANOVA	
		F value	P value
18S 1	Day	1.234	0.273
	Tide	0.967	0.388
	Depth	3.717	0.061
18S 2	Day	0.475	0.494
	Tide	0.144	0.866
	Depth	2.449	0.125
COI 1	Day	0.001	0.994
	Tide	0.744	0.482
	Depth	0.260	0.613
COI 2	Day	0.002	0.961
	Tide	0.058	0.944
	Depth	0.666	0.419

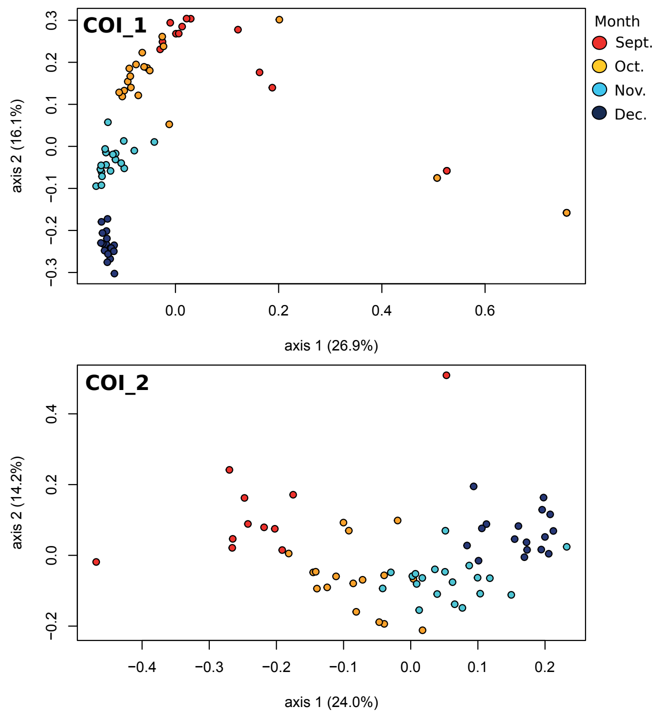

Figure 8. Principal coordinate analyses (PCoA) of eDNA marine metazoans for Churchill harbor annual variation. The eDNA method used the primers COI1 (mlCOIintF-jgHCO2198: left column of each phylum) and COI2 (LCO1490-ill_C_R: right column of each phylum) primer sets separately.

A strong eDNA seasonal variation was found based on patterns observed during the four months studied. In the PCoA results (Figure 8), the eDNA samples are clustering according to the four months. Moreover, these clusters are following a trend of continuity from September to December suggesting a transition from the summer marine community to the winter marine community. At the phylum level, the Arthropoda and Porifera communities are favoriting in December whereas the number of Annelida community decreases in November but increases in December. This December increase could be due to the eDNA preservation under the ice cover.

There is a high variability by phyla among the three years where the marine communities were sampled in the same location within Port of Churchill for the same month (Figure 9). In fact, the phylum Arthropoda, Mollusca and Annelida are more represented for the year 2015, 2016 and 2017 respectively.

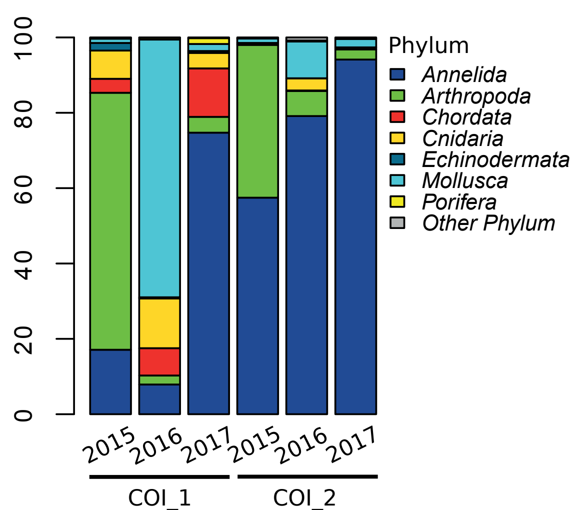

Figure 9. eDNA taxonomic composition at the phylum level for Churchill harbor change season variation. The eDNA method used the primers COI1 (mlCOIintF-jgHCO2198: left column of each phylum) and COI2 (LCO1490-ill_C_R: right column of each phylum) primer sets separately.

Water vs sediment eDNA

The first Arctic eDNA species list collected in sediments is provided in the supplementary Table S1 (availaible on request at arcticnet@arcticnet.ulaval.ca).

Results show that eDNA in sediment increase species richness record (Figure 10). In fact, the number of OTUs from subtidal and intertidal sediments eDNA combined is higher than the number of OTUs from water eDNA. The first results support the hypothesis than the degradation rate of sediment eDNA is slower than the degradation rate of water eDNA.

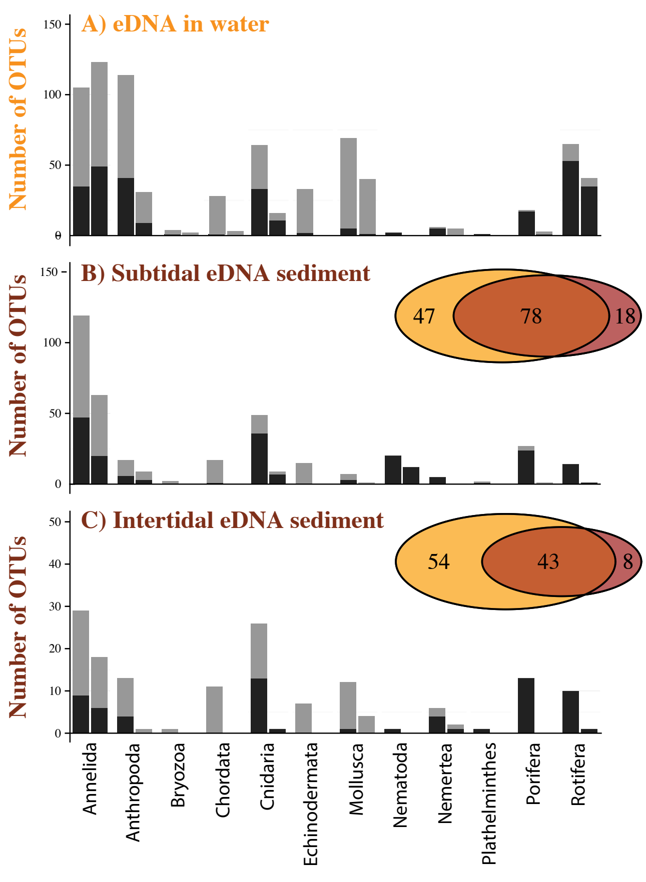

Figure 10. Venn diagram showing the shared species between eDNA in water and in sediment for subtidal and intertidal zones in Deception Bay. The number of Operational taxonomic units (OTU) identified at the species level (black: ≥ 97% identity) relative to those identified below the species level (gray: ≥ 85% and < 97% identity) for each phylum and from the COI1 (mlCOIintF-jgHCO2198: left column of each phylum) and COI2 (LCO1490-ill_C_R: right column of each phylum) primer sets separately.

Bulk vs eDNA

All phyla detected using morphologically identified zooplankton and bulk zooplankton metabarcoding were also detected using eDNA (Figure 11). Phyla with short planktonic stages were better detected using eDNA. A large number of species detected using eDNA was not detected by bulk zooplankton metabarcoding, especially in estuarine ecosystem; likely due to the transport of eDNA in surface water in estuarine ecosystem compared to marine ecosystem. In marine system, 57% community composition was similar between eDNA and bulk zooplankton metabarcoding (Figure 11; Venn diagram), suggesting that 43% species detected using eDNA is due to organic matter released by adults/recruits. In contrast, in estuarine system, only 40% community composition was similar between eDNA and bulk zooplankton metabarcoding, 30% from eDNA released by adults and recruits and 30% are from freshwater eDNA income. Those proportion are thus likely to vary with water river discharged in estuaries due to eDNA transport from the river, eDNA degradation rate (e.g. climate warming) and tide.

Goal 3

Our projects related to community-based eDNA monitoring network has reached a broad public interest. We observed a growing enthusiasm to participate to the eDNA sample collection, as such that eDNA collection to study seasonal variation has been entirely collected by northern community in 2017. New additional DFO funding has been obtained to pursue eDNA trainings in the Arctic.

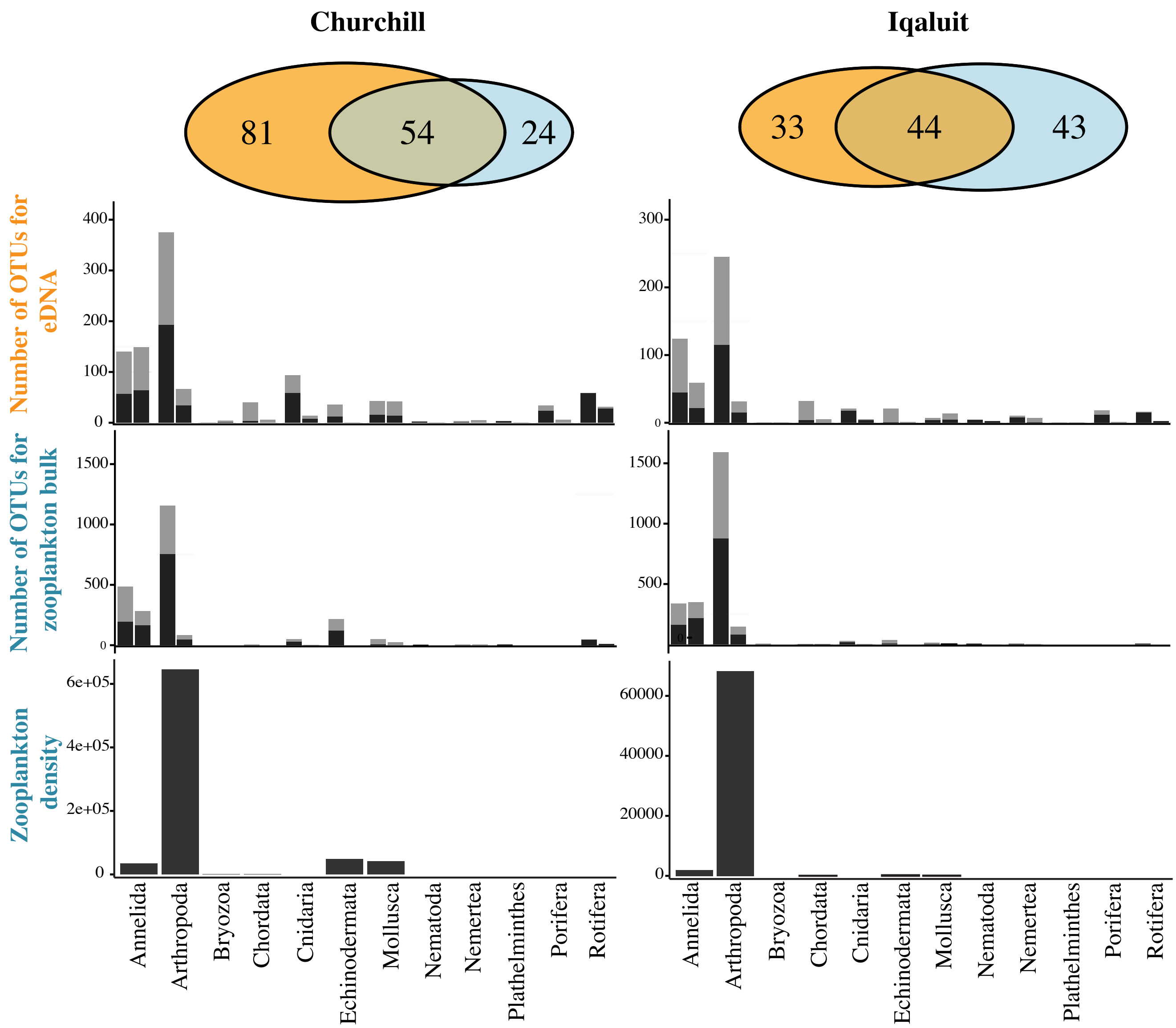

Figure 11. Venn diagram showing the shared species between eDNA and zooplankton metabarcoding. The number of Operational taxonomic units (OTU) identified at the species level (black: ≥ 97% identity) relative to those identified below the species level (gray: ≥ 85% and < 97% identity) for each phylum and from the COI1 (mlCOIintF-jgHCO2198: left column of each phylum) and COI2 (LCO1490-ill_C_R: right column of each phylum) primer sets separately for eDNA and zooplankton metabarcoding for both Churchill and Iqaluit and the zooplankton density identified by classical taxonomy (i.e. morphology).

Goal 4

In summary, we conclude that eDNA metabarcoding surveys can reveal global similarity patterns among ports across a broad array of taxa and greatly facilitate biodiversity research in these key habitats. Based on our results (see 2017 report), we make the following recommendations for future port eDNA metabarcoding surveys: standardize eDNA collection, extraction, and sequencing protocols to maximize biodiversity pattern inference across sites. More precisely, the recommendations are:

1. Use multiple primer sets to enhance species detection, as the COI and 18S primers used here detected different NIS.
2. Given the observed heterogeneity of metazoan MOTUs (molecular operational taxonomic units) across samples within some sites, we recommend collecting at least 15 x 250 mL samples per site to estimate metazoan MOTU richness and nine samples for community dissimilarity estimation. Further research is needed to determine how much of this heterogeneity is due to PCR variation versus spatial aggregation of eDNA.
3. Multiple sites need to be sampled to capture the full biodiversity of a port.
4. Sequence each sample at a depth of 150,000 reads when possible, as this yield ~80% of estimated richness in most samples. For community dissimilarity estimation, lower read depths of 10,000 and 40,000 reads per sample are needed for 18S and COI primers, respectively. The depth needed for less diverse sites or more specific primers is probably less, but this should be beforehand by over-sequencing a few samples. Species assignments can be informative but should be treated with caution given known errors in sequencing and reference libraries.

DISCUSSION

The implementation of biodiversity monitoring is particularly crucial to maintain the integrity of Arctic marine ecosystems in the context of climate change. Outcomes from this project show that environmental DNA (eDNA) metabarcoding has the potential to greatly enhance our understanding of Arctic global biodiversity patterns and inform national and international practices and policies for reducing invasions from ballast water and vessel biofouling. Here, we built the first invertebrate and fish DNA sequence database for Arctic ports, which will provide a baseline for rapid detection of coastal biodiversity shifts (e.g. native species loss/declines, NIS introductions/range expansions). In addition, we evaluate the spatio-temporal eDNA variation and show improved efficacy of eDNA monitoring surveillance when sampling is conducted under-ice cover. Conclusions are based on large datasets within five sensitive Arctic areas (marine and estuarine) among three different depths in the water column, tide pools and different tide and seasons.

Temporal and spatial variation

Standardized port eDNA metabarcoding surveys could greatly increase our understanding of biodiversity in these dynamic habitats. However, developing a standardized method that is applicable is challenging because environmental factors vary considerably in, complexity, hydrodynamics, tide and seasons. Those variations may confound comparisons of species richness and community similarity and, if not adequately considered, prevent accurate understanding of biodiversity changes. Little is known about the ecology of eDNA —that is the interactions between extra-organismal genetic material and its environment [16] — which is fundamental for characterizing large-scale biodiversity patterns using eDNA metabarcoding. Our results clearly show that metazoan eDNA distribution in Arctic coastal environments has significant temporal and spatial variation. Here we present the first study characterizing spatio-temporal eDNA variation in Arctic ecosystem.

Spatial variation highlighted an important differentiation among latitudinal gradients driven by environmental factors such as temperature and pH [17]. Although eDNA is expected to be highly dispersed in cold and dynamic environments, our results show clear horizontal and vertical eDNA heterogeneity within ports. Our data support the idea that in estuarine conditions, such as Churchill, the freshwater flow from the river over long distances may contribute to increasing the diversity in the surface water layer (e.g., [18, 19]). Community changes related to eDNA composition thus need to integrate information on temporal variation in river discharge. Moreover, our results show that tides may modify differences in eDNA composition between the water column and tide pools.

This study is also the first characterizing combined temporal eDNA effects including annual, season and tide effects. Whereas our results showed a strong vertical eDNA distribution in estuarine ecosystem due to the river outcome, they also reveal a strong tide effect on phyla detection (Figure 5). Further research is however needed to elucidate factors driving the strong variability observed among days. More precisely, we demonstrated that the freshwater eDNA from the river was added to the marine eDNA increasing the diversity in surface water in an Arctic estuarine ecosystem. The latter is likely partly due to a low degradation of eDNA in cold water increasing eDNA transport over large distance [18, 19]. Results on tide variation highlighted three distinct groups of marine biodiversity. The low tide and the high tide groups might be represented in majority by freshwater and marine eDNA communities respectively, whereas, the middle tide group could be an intermediary between the fresh and salt water biodiversity.

Coastal biodiversity monitoring in the Arctic using traditional sampling approaches is generally limited to summer. In contrast to traditional surveys, the quality of eDNA surveys might actually improve under the ice cover due to the limited UV exposure and cold water temperature, hence promoting eDNA preservation and detection [20]. On the other hand, cold temperatures are expected to reduce the metabolism of species and associated eDNA release/detection [21]. Here, eDNA metabarcoding of water collected under ice cover detected greater species richness than summer water collections. This is particularly relevant because the use of eDNA could expand the time window to survey coastal biodiversity in the Arctic. Our recent seasonal study helped characterize the marine community structure transition from summer-winter which we hope will allow for the development and testing new hypotheses about reproduction cycle among phyla in the Arctic ecosystem.

Although the temporal variation of eDNA is a limiting factor for biomonitoring, our results show that monthly biomonitoring could be perfectly adapted to the Arctic system. In fact, we observed a reliable pattern for seasonal variation with the increasing or decreasing of species which could be adapted to AIS.

Comparison with classical methods

The use of classical method for biomonitoring marine diversity is limited to the summer season whereas the eDNA method could be implemented at all times of the year. Therefore, the development and the standardization of the eDNA method could expand the time window to survey marine biodiversity in the Arctic. The comparison between classical and eDNA methods show an excellent correlation for the bulk plankton. Here, it is noteworthy that the Tara Expeditions in the Arctic has substantially completed the genomic database for plankton in the Arctic [22]. Therefore, once the public genomic database becomes as complete as possible, the eDNA has potential to be as reliable as the classical methods. In contrast, the comparison between classical and eDNA methods with benthos show a reduced diversity with the eDNA method. Currently, a high proportion of the Arctic species have not been sequenced yet. However, following considerable barcoding effort, our samples could be reanalyzed once the Arctic marine biodiversity reference sequences are available in a public database. For this purpose, benthic specimens collected in harbors were preserved to be used for future barcoding when the funds will be available.

CONCLUSION

Our main objective was to adapt the metabarcoding technique to the Arctic system for improving the efficiency of biomonitoring of the marine biodiversity in the context of climate change and prevent the introduction of AIS. We validated the potential of the eDNA method for detection of both native and invasive taxa by developing and testing of different sets of primers. We also developed in silico a bio-informatics program, a new sampling method and preservation as well as a DNA extraction. The important reduction in costs that this new method allowed us to significantly increase the sample size. The simplicity of the new sampling and preservation method allowed inexperienced collaborators to collect additional eDNA samples and as consequence, favored the development of a community-based monitoring program. Furthermore, we continuously improved the eDNA method in vivo by optimizing water sampling strategies and the bio-informatics program throughout our spatio-temporal eDNA studies. We also provided recommendations for sampling and interpreting the eDNA method from commercial ports and continued to support the development of a community based monitoring. In addition to testing and comparing eDNA performance, we showed the importance of continuing to increase the content of public genomic databases.

By overcoming methodological issues and improving knowledge about the ecology of eDNA in coastal areas, this project creates the opportunity for future monitoring of metazoan coastal diversity in highly vulnerable ecosystems such as Arctic commercial ports. As the eDNA method progresses, the use of eDNA is likely to expand and become a catalyst for increased research on coastal biodiversity, ecosystem services, and sustainability, particularly in remote regions of the world such as the Canadian Arctic. However, spatio-temporal dimensions need to be considered in standardizing and optimizing the assessment of marine biodiversity using eDNA. Information presented here on both the potential of eDNA to target biodiversity and the behavior of eDNA, particularly in novel environments such as Arctic coastal marine areas, are timely and important for evaluating biodiversity change. Given its ever increasing breath of applications, including for policy decisions and fields outside of the life sciences, this pioneer Arctic eDNA research will be of interest for a wide range of disciplines including ecology (population, community and eDNA), conservation biology, risk assessment, species distribution modeling and ecosystem dynamics.

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REFERENCES

1. Parker IM, Simberloff D, Lonsdale WM, Goodell K: Impact: toward a framework for understanding the ecological effects of invaders. Springer 1999.
2. Grosholz E: Ecological and evolutionary consequences of coastal invasions. Elsevier 2002.
3. ACIA A: Impacts of a Warming Arctic: Arctic Climate Impact Assessment. 2004.
4. Chan FT, Bailey SA, Wiley CJ, MacIsaac HJ: Relative risk assessment for ballast-mediated invasions at Canadian Arctic ports. Springer 2013.
5. Niimi AJ: Environmental and economic factors can increase the risk of exotic species introductions to the arctic region through increased ballast water discharge. Springer 2004.
6. Taberlet P, Coissac E, Hajibabaei M, Rieseberg LH: Environmental DNA. Molecular ecology 2012, 21:1789–1793.
7. Thomsen P, Kielgast J, Iversen LL: Monitoring endangered freshwater biodiversity using environmental DNA. Molecular ecology 2012, 21:2565.
8. Shaw J, Clarke LJ, Wedderburn SD, Barnes TC: Comparison of environmental DNA metabarcoding and conventional fish survey methods in a river system. Elsevier 2016.
9. Port JA, O'Donnell JL, Romero-Maraccini OC: Assessing vertebrate biodiversity in a kelp forest ecosystem using environmental DNA. Molecular ecology 2016, 25:527.
10. Valentini A, Taberlet P, Miaud C, Civade R: Next-generation monitoring of aquatic biodiversity using environmental DNA metabarcoding. Molecular ecology 2016, 25:929.
11. Olds BP, Jerde CL, Renshaw MA, Li Y: Estimating species richness using environmental DNA. Ecology and evolution 2016, 6:4214.
12. Lodge DM, Turner CR, Jerde CL, Barnes MA: Conservation in a cup of water: estimating biodiversity and population abundance from environmental DNA. Molecular ecology 2012, 21:2555.
13. Thomsen PF, Willerslev E: Environmental DNA– An emerging tool in conservation for monitoring past and present biodiversity. Elsevier 2015.
14. Mahé F, Rognes T, Quince C, de Vargas C: Swarm v2: highly-scalable and high-resolution amplicon clustering. peerjcom 2015.

15. Rognes T, Flouri T, Nichols B, Quince C, Mahé F: VSEARCH: a versatile open source tool for metagenomics. peerjcom 2016.

16. Barnes MA, Turner CR: The ecology of environmental DNA and implications for conservation genetics. Springer 2016.

17. Mecklenburg CW, Møller PR, Steinke D: Biodiversity of Arctic Marine Fishes: Taxonomy and Zoogeography. Mar Biodivers 41, 109-140. 2011.

18. Jane SF, Wilcox TM, McKelvey KS, Young MK, Schwartz MK, Lowe WH, Letcher BH, Whiteley AR: Distance, flow and PCR inhibition: eDNA dynamics in two headwater streams. Molecular Ecology Resources 2014, 15:216–227.

19. Deiner K, Altermatt F: Transport distance of invertebrate environmental DNA in a natural river. PloS one 2014, 9:e88786.

20. Barnes MA, Turner CR, Jerde CL, Renshaw MA, Chadderton WL, Lodge DM: Environmental conditions influence eDNA persistence in aquatic systems. Environ Sci Technol 2014, 48:1819–1827.

21. Lacoursière-Roussel A, Côté G: Quantifying relative fish abundance with eDNA: a promising tool for fisheries management. Wiley Online Library 2016, 53:1148.

22. Pesant S, Not F, Picheral M, Kandels S: Open science resources for the discovery and analysis of Tara Oceans data. naturecom 2015.

PUBLICATIONS

Deiner K, Bik H, Mächler E, Seymour M, Lacoursière-Roussel A, Altermatt F, Creer S, Bista I, Lodge D, de Vere N, Pfrender M, Bernatchez L (2017) Environmental DNA metabarcoding: transforming how we survey animal and plant communities. Molecular Ecology 26: 5872-5895.

Howland, K, Lacoursière-Roussel A, Bernatchez L, Archambault P, Cypihot, V, McKindsey C, Simard N, Goldsmit J, Lodge D, Grey E, Rochon A, Winkler G. Difallah F, Dispas A. Development of community-based monitoring for aquatic invasive species (AIS) in the Canadian Arctic - preparing for increased shipping related to resource development and climate change. Polar Knowledge Canada Interim Report: PKC-NST-1617-0016.

Lacoursière-Roussel A, Deiner K, Bernatchez L (submitted) eDNA are molecules in environment. Perspective: Science.

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

Project Team

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ABSTRACT

Remote sensing, the science of aerial or satellite data capture of the earth, provides crucial information for monitoring oceans. Vast amounts of data are generated and computer-based algorithms to identify ice and oil slicks are urgently needed. For example, using radar-based images from the Canadian RADARSAT-II satellite, Canadian Ice Service (CIS) personnel manually interpret 4000 scenes annually, providing ice maps over huge (500 km by 500 km) regions. These maps can be used to infer ice thickness and strength to facilitate decision support systems for shipping and icebreaking. Using finer scale imagery, local ice maps for Arctic communities can be provided to aid hunting and transportation in ice regimes. CIS runs 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 radar-based imagery for ice mapping and detecting oil spill candidates. The challenge involves sensor limitations and environment variability that confuse ice and open water and confuse oil slicks with other natural phenomena. This project's algorithm design will also support the new Canadian satellites, known as the RADARSAT Constellation Mission (RCM), planned for launch in 2018.

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.
- In 2018, Canada is launching the RADARSAT Constellation Mission which will provide new types of synthetic aperture radar (SAR) satellite imagery called compact polarimetry (CP). Our recent efforts have been focused on evaluating this new data source in comparison to the current data.
- Automated machine learning methods for ice interpretation for rapid and accurate ice map generation are being developed to support navigation and environmental modelling, crucial given the increased volume of data that will be generated from the three RCM satellites.
- A convolutional neural network (CNN) has been developed for automated ice/water segmentation of SAR imagery.
- 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 human and automated recognition is challenging due to winds and oil breakup. Our research is developing novel means to identify oil spill candidates in SAR imagery using machine learning techniques. SAR scenes with demonstrated oil spills have been provided using the Canadian Ice Service (CIS) ISTOP (Integrated Satellite Tracking of Pollution) system.
- A new initiative with Dr. Derek Mueller (Carleton) to evaluate MAGIC algorithms to perform identification and tracking of ice islands is in progress.
- New SAR data at higher resolution compared to that used for operational ice mapping has been provided in the vicinity of the community of Pond Inlet, Nunavut. The goal is to provide ice maps to assist local residents with understanding the changing ice conditions that affect their way of life.
- 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.
- Ship detection using SAR is important for ship tracking, especially with regards to oil spills. Using AIS data for validation, results demonstrate a high accuracy rate with nearly 100% detection of known ships using SAR.
- For the estimation of significant ocean wave height, the new compact polarimetry (CP) channel “RH”, on the upcoming RADARSAT Constellation Mission (RCM), outperforms linear polarizations available on current satellite-based imaging radar instruments, including RADARSAT-2.
- We have actively dialogued with third parties (PCI Geomatica, Canadian Ice Service) with regards to operational and commercial use of algorithms and software developed.
- In-situ ice thickness measurements demonstrate that sea ice thinning continues in the high Arctic.

- Ship-based ice thickness measurements were carried out and provided clear relations between thicker ice and slower sailing speed.

RESEARCH OBJECTIVES

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

1. Conduct research into algorithms to automatically create state-of-the-art simulated SAR images containing ice and oil slicks since such natural 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 GUI tools and data storage to generate ground truth, either in-house or at CIS, derived from SAR scenes that illustrate useful ice types (e.g., multi-year, first year, new) and open water.
4. Develop a new unsupervised scene segmentation algorithm based on the existing IRGS framework using a statistical model for complex compact polarimetry (CP) SAR scenes.
5. Evaluate and compare success of dedicated automated classification algorithms for dual pol, full quad pol, and complex compact polarimetry (CP) SAR scenes.
6. Develop and evaluate automated algorithms for their ability to accurately identify ice categories (multi-year, first year, young, new) and open water, using SAR dual-pol, fine quad-pol, and CP imagery.
7. 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+%.
8. Apply deep learning techniques to the automated interpretation of SAR sea ice imagery. More specifically, use convolutional neural networks (CNNs) to generate improved ice concentration maps, ice/water maps, ice typing maps, and oil slick detection.
9. 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.
10. Assess the ability of MAGIC algorithms to demarcate, classify, and track ice islands in SAR imagery (in collaboration with Dr. Derek Mueller, Carleton University).
11. Apply MAGIC software system to the mapping of ice for local communities. The needs of local communities are quite different than the WMO ice mapping priorities and, in collaboration with CIS, we have started evaluating such data with local Northern community interests in mind.
12. 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.
13. 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.
14. Create partnerships for end use of algorithms developed (PCI Geomatica, ASL Environmental Systems).
15. Develop and test numerical models that are better able to identify ships and icebergs from SAR image data.

16. Develop and test numerical SAR models that improve ocean wave height estimation from SAR image data.
17. Partner with C. Duguay (Geography, University of Waterloo) to study the ability for the MAGIC system to segment SAR lake ice scenes.
18. Provide MAGIC software and machine learning support to Dr. Benoit Montpetit for automated SAR sea-ice scene interpretation.
19. Provide validation data for SAR algorithms through direct, over the ice field measurements.
20. Continue long-term ice thickness observations through field validation research.
21. Apply machine learning methods for the automated counting of whales (belugas and narwhals) based on aerial imagery. This is a new research opportunity introduced by our combined expertise in machine learning, remote sensing, and Arctic experience.

KNOWLEDGE MOBILIZATION

From April 2017 to February 2018, the following mobilization activities took place.

- 15 refereed journal publications submitted, accepted or published.
- Ongoing discussions with other researchers and companies with regards to the use of developed software and knowledge in the field of machine learning applied to remote sensing data.
- Government agencies interested in partnering for enhanced algorithm development and usage.
- Ongoing regular research discussions with the Canadian Ice Service (CIS).
- Feb/Mar 2017: evaluations of MAGIC's IRGS algorithm for unsupervised segmentation of SAR imagery by PCI Geomatica.
- Mar 2017: David Clausi one day research meeting with CIS in Ottawa with two PhD students (M. Xiang, M. Gahnbari) with numerous CIS personnel.
- Apr 2017: half day teleconferencing research meeting between University of Calgary (M. Collins) and University of Waterloo (D. Clausi and HQP) to discuss physical modelling of ocean waves and ship detection using SAR imagery.
- Sept 2017: follow-up phone discussion with D. Flett and T. Zagon to establish research priorities and a plan with CIS.
- Oct 2017: dialogue with and data receipt from T. Fisette (Agriculture and Agri-Food Canada) to support automated approaches for the interpretation of agriculture-based remote sensing imagery.
- Dec 2017: meetings with T. Zagon (CIS) while at ArcticNet AGM.
- Dec 2017: meeting with B. Montpetit (Environment and Climate Change Canada) at ArcticNet AGM after ongoing emails during 2017 with regards to using MAGIC for demarcating ice and water in SAR imagery.
- Dec 2017: request by Fisheries & Oceans (M. Marcoux) to design and develop an automated machine learning approach to count narwhals and belugas in Arctic regions using aerial photography; data has been provided and is currently being assessed for proper algorithmic development.
- Feb 2018: further discussions with B. Montpetit now with regards to usage of CNNs to perform ice/water segmentation of SAR sea ice imagery; paper in progress.

INTRODUCTION

Satellite imagery is the only feasible means for monitoring the vast Arctic. Synthetic aperture radar (SAR) imaging 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 expand with increased Arctic shipping traffic and increased volume of SAR imagery due to the three satellite RADARSAT Constellation Mission (RCM) planned for launch later in 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.

Maritime activities are an important part of the economy for many countries. These activities include fishing, oil production, wind farms, transportation and tourism. Knowledge and prediction of the ocean wave climate is essential for safe maritime operations. Buoys provide a sparse network of direct observations of the wave climate. Satellite synthetic aperture radar (SAR) imagery is particularly useful due to its spatial resolution and its ability to produce maps of wave climate parameters. 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. Success has been 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. Ground truth data provided by field work studies is an important aspect to validate machine learning algorithms.

ACTIVITIES

Use of Deep Learning to Interpret SAR Sea Ice Scenes

- Convolutional neural networks (CNNs), a form of "deep learning", have been investigated to assess their capabilities for estimating ice concentration, binary ice/water classification, and ice typing in SAR imagery.
- We have implemented prototype CNNs for ice/water classification using widely available, and exceptionally noisy, SENTINEL-1 data.
- L. Xu (PDF) is the lead research on this project.

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.
- A course project has developed preliminary algorithms for solving this problem.
- M. Ghanbari and M. Jiang (PhD candidates) conducting research on this topic.

Improving MAGIC Software for Operational Use

- Created software requirements and have identified how to modify the MAGIC software to allow input of 16-bit data.
- Will lead to the ability to perform the first comprehensive evaluation of the impact of n-bit data for scene segmentation. Full dynamic range risks errors due to speckle noise and some quantization may be used to improve segmentation performance so varying the quantization level is of importance.
- This implementation is part of the software development lead up for processing RCM CP data.
- Released new MAGIC version that also included ability to manually adjust output colours on classification results.
- M. Ghanbari and M. Jiang (PhD candidates) are conducting research on this topic.

Compare Simulated CP data for Scene Segmentation

- Converted published RADARSAT-2 quad-pol scenes to simulated compact polarimetry (CP) scenes.
- Compared dual-pol and CP scenes for their classification ability and have submitted a paper on this topic.

- Now comparing quad-pol (using our in-house algorithm, polarIRGS), dual-pol, and CP scenes for their segmentation success.
- In progress of developing a SAR scene segmentation approach using statistics based on complex CP data, similar in approach to polarIRGS which also uses complex data.
- Compare dual-pol, complex quad-pol, complex CP, and features derived from simulated CP for SAR scene labelling (following segmentation success).
- M. Ghanbari (PhD candidate) has been actively completing this research.

Multi-Class Ice Classification

- 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 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.

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.
- A journal publication was accepted during this reporting year that uses novel active learning approach for classifying dark spots as oil spills. This was a follow-on to an earlier publication of ours that first identified the dark spots as potential oil spills.
- Research lead by Y. Cao (visiting scholar) and L. Xu (PDF).

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, under co-supervision with C. Duguay (UWaterloo).
- J. Wang (MSc candidate) has successfully defended her MSc thesis based on this research; MAGIC algorithms were used in direct support of this research.

- Lake ice was accurately classified for ice/water but not as well classified for ice type classification using Lake Erie for testing.
- M. Hoekstra (MSc candidate) is applying a similar approach to a different data set based on Great Slave and Great Bear lakes.
- A pair of refereed conference papers have been produced from this research.

Provision of Novel Ice Maps for Support of Northern Communities

- Canadian Ice Service has an active interest in providing dedicated ice map products for northern communities.
- We have received a set of data from CIS (for Pond Inlet) which is a different RADARSAT-2 mode and data format than used for operational ice map generation. This data has a finer resolution of a shorter swath for direct support of on-ice navigation and safety needs of local communities.
- The automated land masking system is not working accurately for these different RADARSAT-2 modes leading to land maps that are not properly registered to the SAR imagery so that some land is being included in the ocean regions, causing segmentation errors. We are working on resolving these issues.
- 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. CIS has already created prototype ice maps that will be used to support these revised classifications.

Numerical Modelling of SAR Backscatter for Ocean Wave Height Estimation

- Explored the effect of polarization and incidence angle of the CWAVE model by using Radarsat-2 fine quad image data.
- Experimented with standard linear regression, using a subset of terms selected by the elastic net algorithm, and shallow neural networks.

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.

Machine Learning Identification of Whales in Aerial Photos

- Fisheries and Oceans Canada (M. Marcoux) has requested assistance with determining the abundance of narwhal and beluga populations from aerial photographs.
- Currently, aerial surveys are performed capturing 1000s of contiguous images that are then manually assessed for counting narwhal or beluga whales (depending on the location of the survey).
- We are investigating the use of machine learning methods (convolutional neural networks, CNNs) to automate this process for the rapid demarcation of potential whales.
- Such a process will greatly facilitate the speed of assessing the 1000s of photos and we expect that results would be turned around in a more favorable time period (<1 month).

- We received three sets of data with labelled ground truth (i.e., whales manually identified) from previous years of field works. A PDF (L. Yu) has learned how to read and process this extensive data set. An MASc student (V. Sankar) is starting the process of data manipulation for feeding into machine learning algorithms and experiments are being planned.
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Field Work Activities

- Ice thickness surveys were carried out over the Beaufort Sea and north of Ellesmere Island in April 2017. These were led by York University (C. Haas) and used aircraft for electromagnetic surveying and for landings on sea ice.
- Ship-based ice thickness measurements were carried out in the Labrador Sea in February 2017. There were led by York University in close collaboration with Fednav, using their icebreaking cargo ship MV *Arctic*.

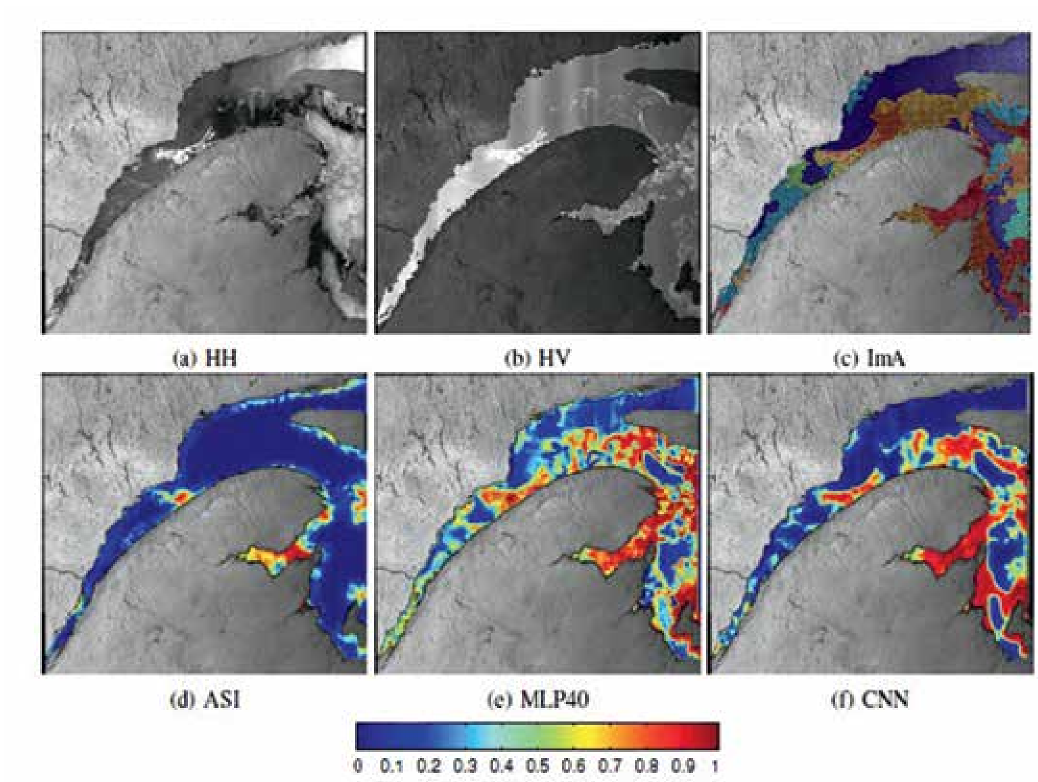

Figure 1. The ice concentration estimation result by CNN compared to other methods for generating ice concentration estimates based on a SAR scene. (a) and (b) represent the HH and HV polarizations, (c) is the corresponding image analysis chart (ImA), (d) represents the results using the known ASI algorithm, (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.

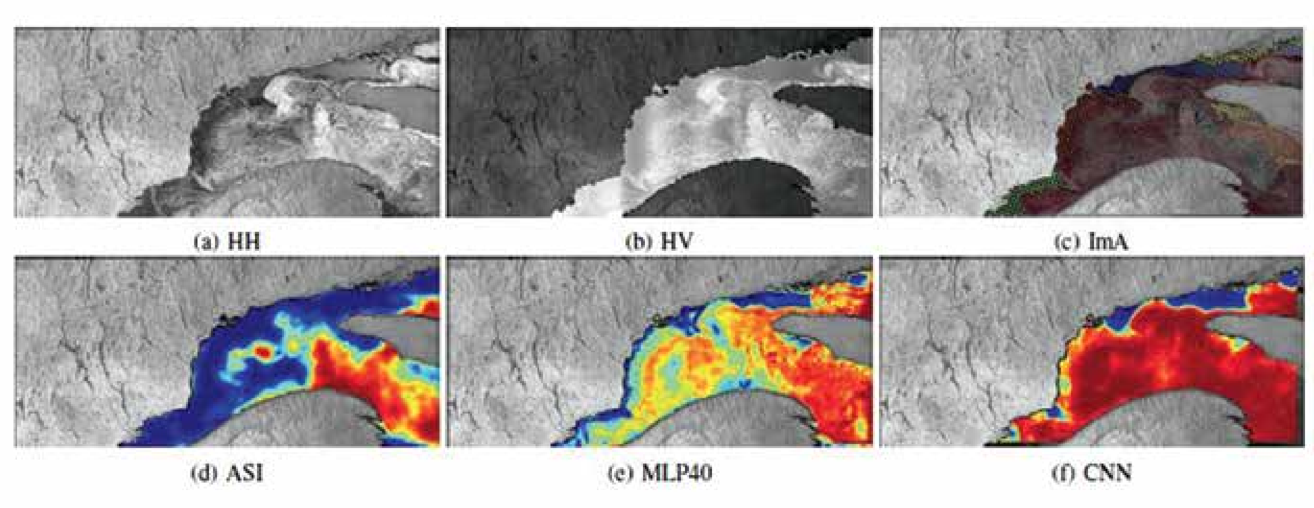

Figure 2. Similar to Figure 1, but using a different SAR scene. The results again demonstrate the superiority of the CNN method to produce more detailed ice concentration maps. The ASI method completely over represents water regions, the MLP40 does not indicate sufficiently high ice concentrations especially near the middle of the scene.

RESULTS

Convolutional Neural Networks (CNNs) 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. 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 (Figures 1 and 2). The CNN algorithm has been successfully applied to the estimation of ice concentration (Wang et al., 2016a; Wang et al., 2016b).

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 5 scenes and tested successfully on 15 scenes. This preliminary study encourages us to put more resources into CNN evaluation for SAR scene analysis.

Oil Spills – Dark Spot Detection and Classification

This research is a two-step process. First, potential oil spills (“candidates”) are identified in a SAR scene. Then, using features derived from the candidate, a classification system is developed and used to determine if the candidate is a true oil spill.

The detection of oil spill candidates using SAR is difficult due to SAR sensor limitations and the complex marine environment. To address this problem, the large-scale spatial-contextual information in SAR imagery has to be utilized to increase the class separability between oil spill candidate and the background (Xu, et al., 2016a). We developed a stochastic fully-connected continuous conditional random field (SFCCRF) approach to model the SAR image and perform soft-label inference, leading to

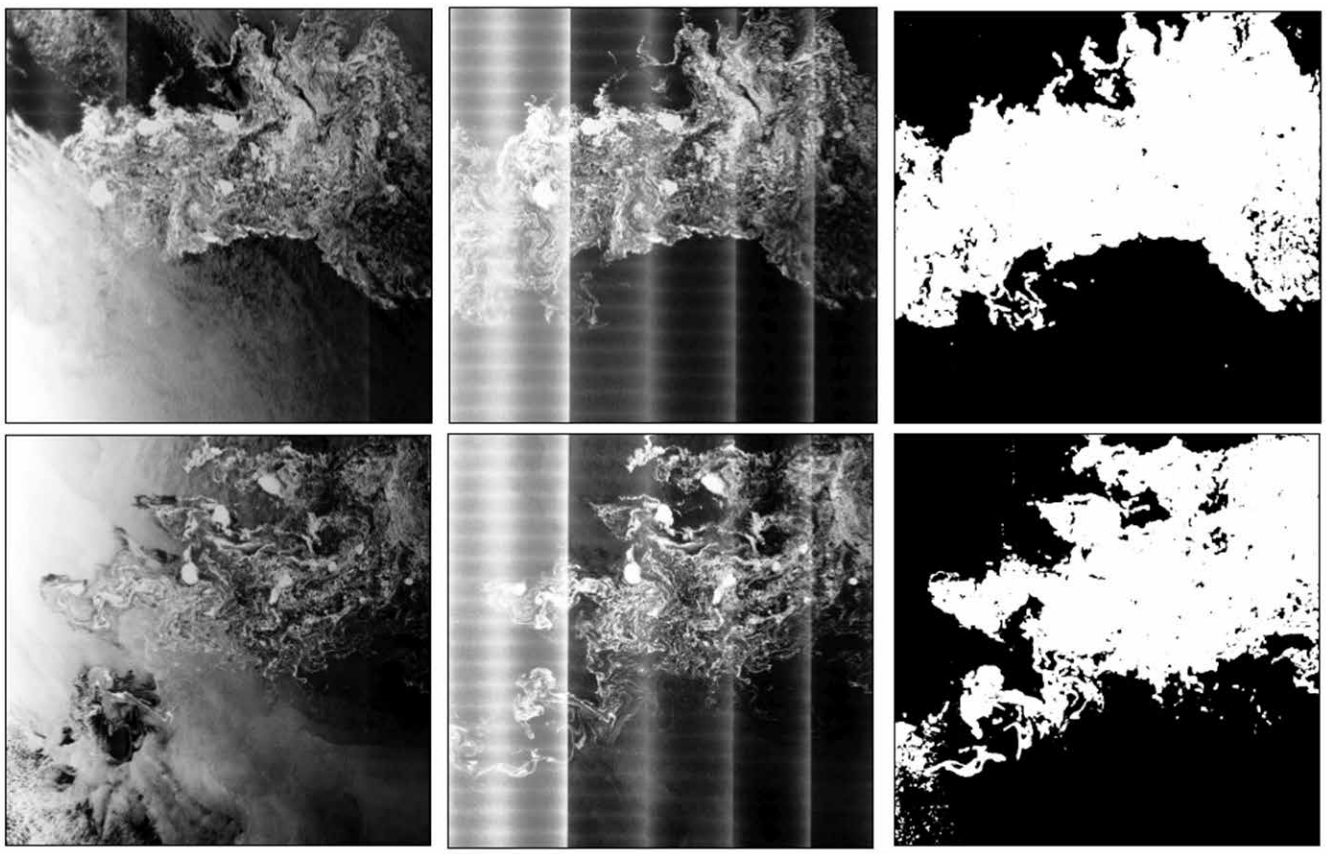

Figure 3. Two examples of successful application of a trained CNN applied to two ENVISAT SAR scenes. First column is the HH-pol, second column is the HV-pol, and the third column is the output of the CNN successfully identifying ice and water regardless of the high noise content of the HV-pol. This is a demonstration of the success of using novel machine learning methods to the problem of binary ice/water segmentation and classification.

an efficient detection algorithm. Instead of treating all pixels in SAR imagery as being connected, SFCCRF determines the connectivity of two pixels in a stochastic manner based on their proximity in both feature space and image space. Since SFCCRF provides an efficient and effective way for modeling the large-scale spatial correlation effect, the resulting soft-labels can resist the influence of speckle noise and highlight the difference between oil spill candidates and the background. Oil spill candidate detection is achieved by binarizing the soft-labels estimated by SFCCRF. The proposed algorithm is tested on both simulated and real SAR imagery. The results show that SFCCRF can delineate the oil spill candidates with low commission and omission error rates. The conditional random field (CRF) approach is novel compared to the basic thresholding approaches currently found in the research literature (Figure 4).

Our research found a more cost-effective method for training oil spill classification systems by introducing active learning (AL) so that appropriate classifiers could learn with reduced number of labeled samples (Cao et al., 2016; Cao et al., 2017). A dataset provided by CIS with 143 oil spills and 124 look-alikes from 198 RADARSAT images covering the east and west coasts of Canada from 2004 to 2013 was used. Six uncertainty-based active sample selecting (ACS) methods were designed to choose the most informative samples. A method for reducing information redundancy amongst the selected samples and a

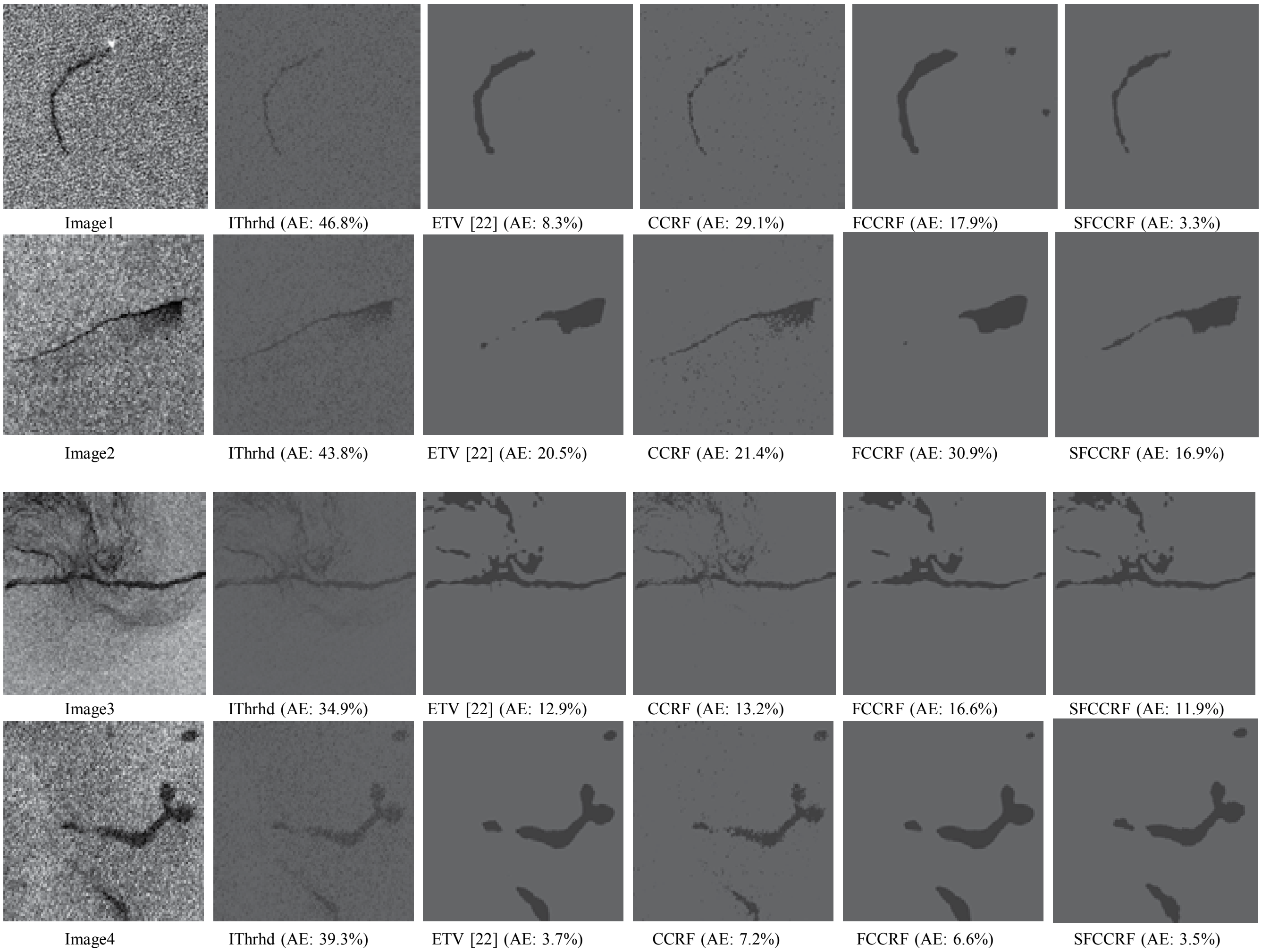

Figure 4. Detection of oil spill candidates by five different methods on four images. Comparing with the other methods, the proposed SFCCRF method is less affected by the background and target heterogeneities, and in the meantime can more accurately identify the boundaries and the linear targets.

method with varying sample preference are considered. Four classifiers (k-nearest neighbor, support vector machine, linear discriminant analysis and decision tree) were coupled with ACS methods to explore the interaction and possible preference between classifiers and ACS methods. Overall, AL proves its strong potential with 4% to 78% reduction on the number of training samples in different settings. The SVM classifier shows to be the best one for using in the AL framework (Figure 5).

Simulating 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 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

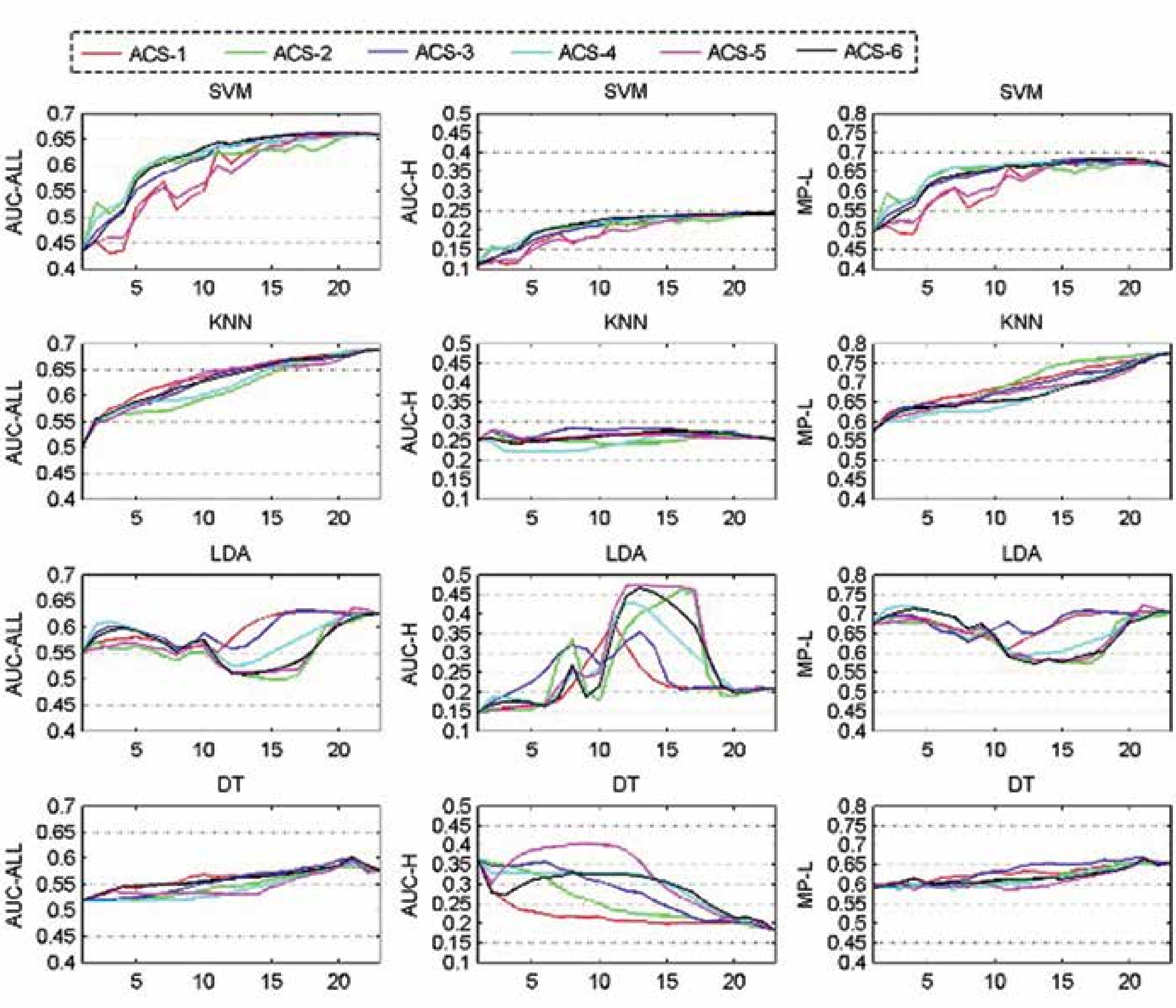

Figure 5. Graphs of performance evolving over iterations (horizontal axis) of active learning methods with various classifiers (SVM, KNN, LDA, and DT). The terms AUC-ALL, AUC-H, and MP-L are various measures of overall performance.

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 6).

Lake Ice Classification Using MAGIC

Lake ice is an indicator of climate change. SAR satellite imagery is routinely used to monitor ice on large lakes. Instead of manually interpreting the lake ice concentration and types, we applied automated sea-ice segmentation methods to

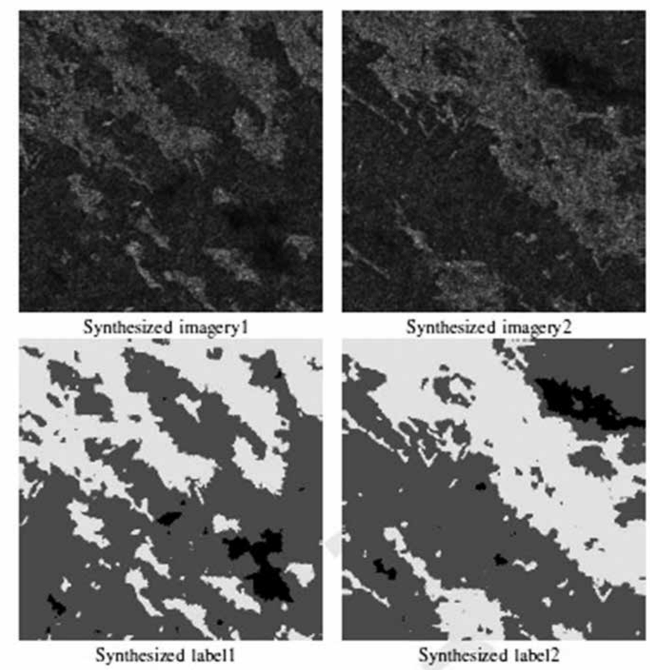

Figure 6. Two successful examples of synthesized SAR scenes with ice, water, and oil and accompanying scene with labels.

the lake ice data. We used the "glocal" approach employing the IRGS unsupervised segmentation algorithm in the MAGIC software system. Successfully testing has been conducted on Great Slave and Great Bear lakes as well as Lake Erie. MAGIC software and algorithms were used by a pair of Geography graduate students (M. Hoekstra, J. Wang) applied to the lake ice. The classification process was able to demarcate ice from open water, but was not as successful identifying individual ice types (Figure 7).

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

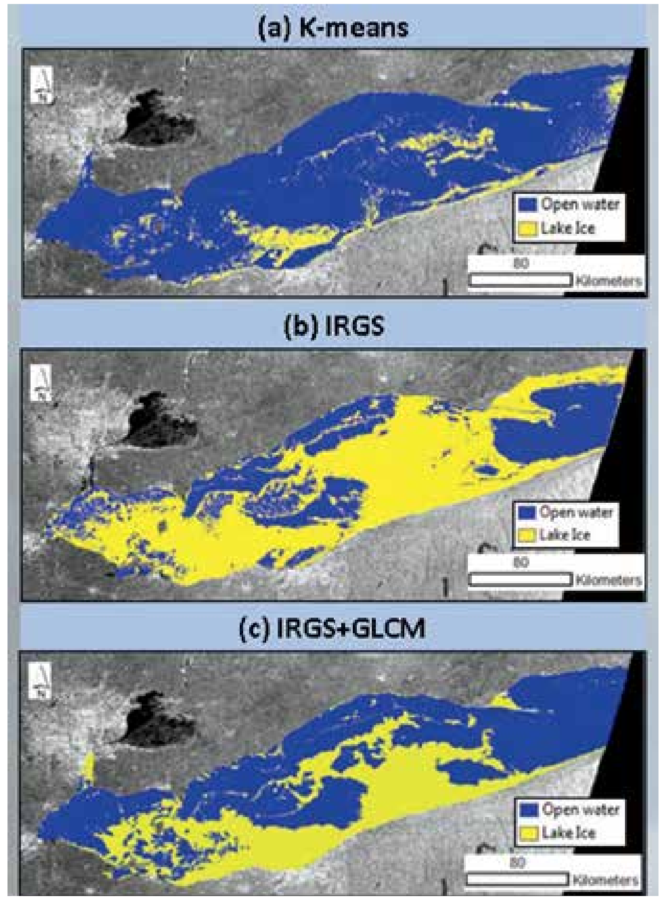

Figure 7. A comparison of classification tests for lake ice SAR scene. K-means, IRGS, and IRGS + texture features are compared with the IRGS alone showing the best performance.

this method on SAR sea ice imagery (Xu et al., 2016d). The classification of pixels in remotely sensed imagery (RSI) into land cover classes typically requires knowing the labels of some image pixels for model training. However, accurate pixel-level label information is usually difficult and expensive to acquire, which restricts the applicability of supervised image classification methods. In contrast, the region labels information that specifies which classes are contained in a region of the image is easier to acquire and less susceptible to identification errors. To utilize the region label information for remotely sensed image classification, we developed a weakly-supervised Image classification approach using Label

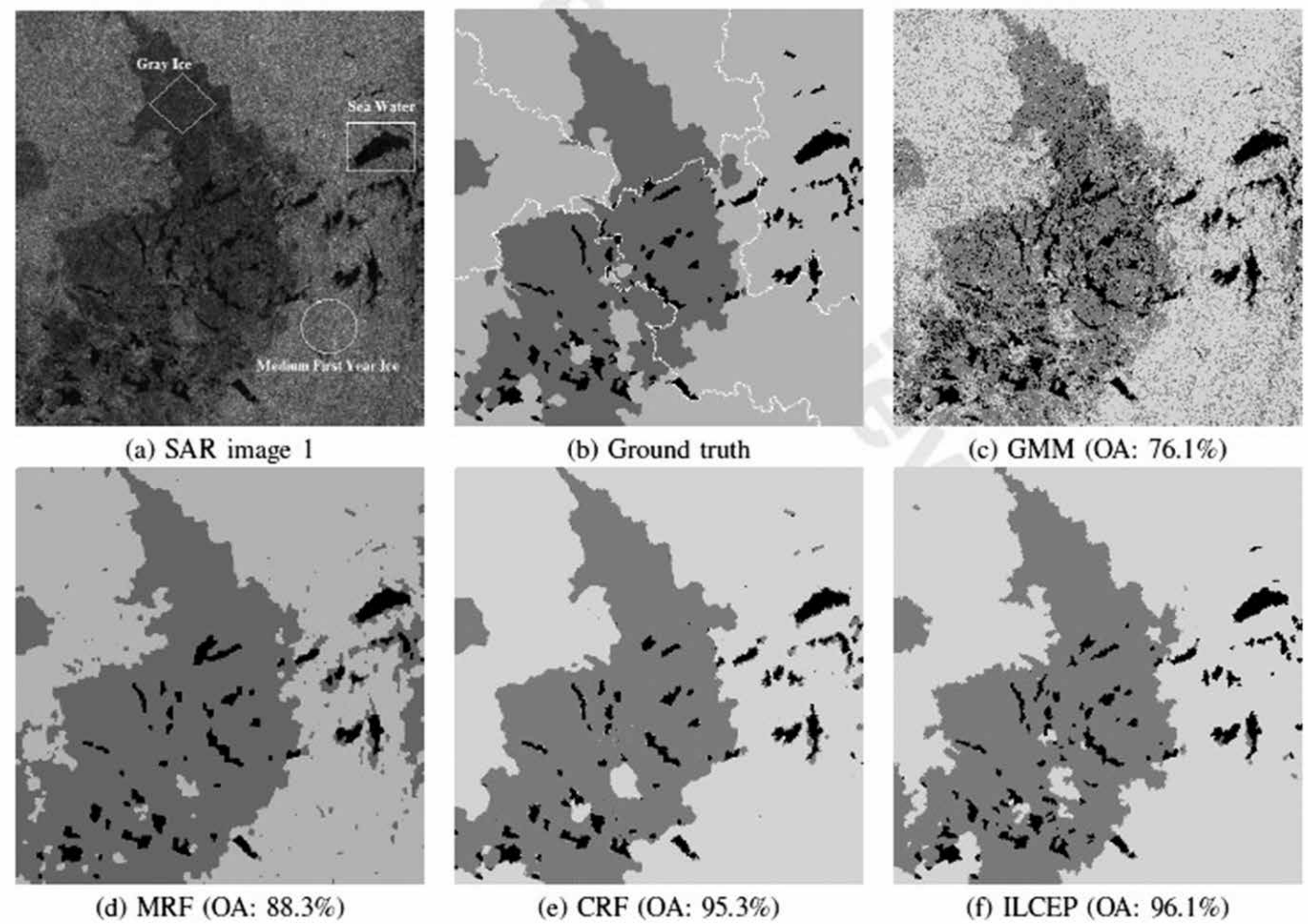

Figure 8. A SAR sea ice scene used for comparison of four different approaches: Gaussian mixture model (GMM), Markov random field (MRF), conditional random field (CRF), and our new method, ILCEP (Image classification using Label Constraint and Edge Penalty). The latter is best able to segment boundaries effectively and properly label the regions.

Constraint and Edge Penalty (ILCEP). Experiments on both simulated and real SAR images demonstrate that the approach can achieve high classification accuracy by knowing only the region-level label information (Figure 8).

Full-Scene Region-Based Classification of CP Scenes Compared to Dual-Pol

The expected RCM compact polarimetry (CP) SAR imagery (to be launched in 2018) will necessitate exploring new automatic classification methods. A sea-ice type classification method using CP data for discriminating between ice types has been designed and implemented. The iterative region growing using semantics (IRGS) segmentation algorithm is first applied to the channel intensity images to identify homogeneous regions ensuring each region contains only one sea-ice type. Then, a supervised support vector machine (SVM) classification method is employed to obtain the ice-type labels. Two CP data sets are simulated from two sets of fine quad-polarimetry RADARSAT-2 SAR data and used for training and testing the proposed algorithm. The classification accuracy assessments show that using only two CP channel intensities, we obtain noticeably better results as compared to those obtained using

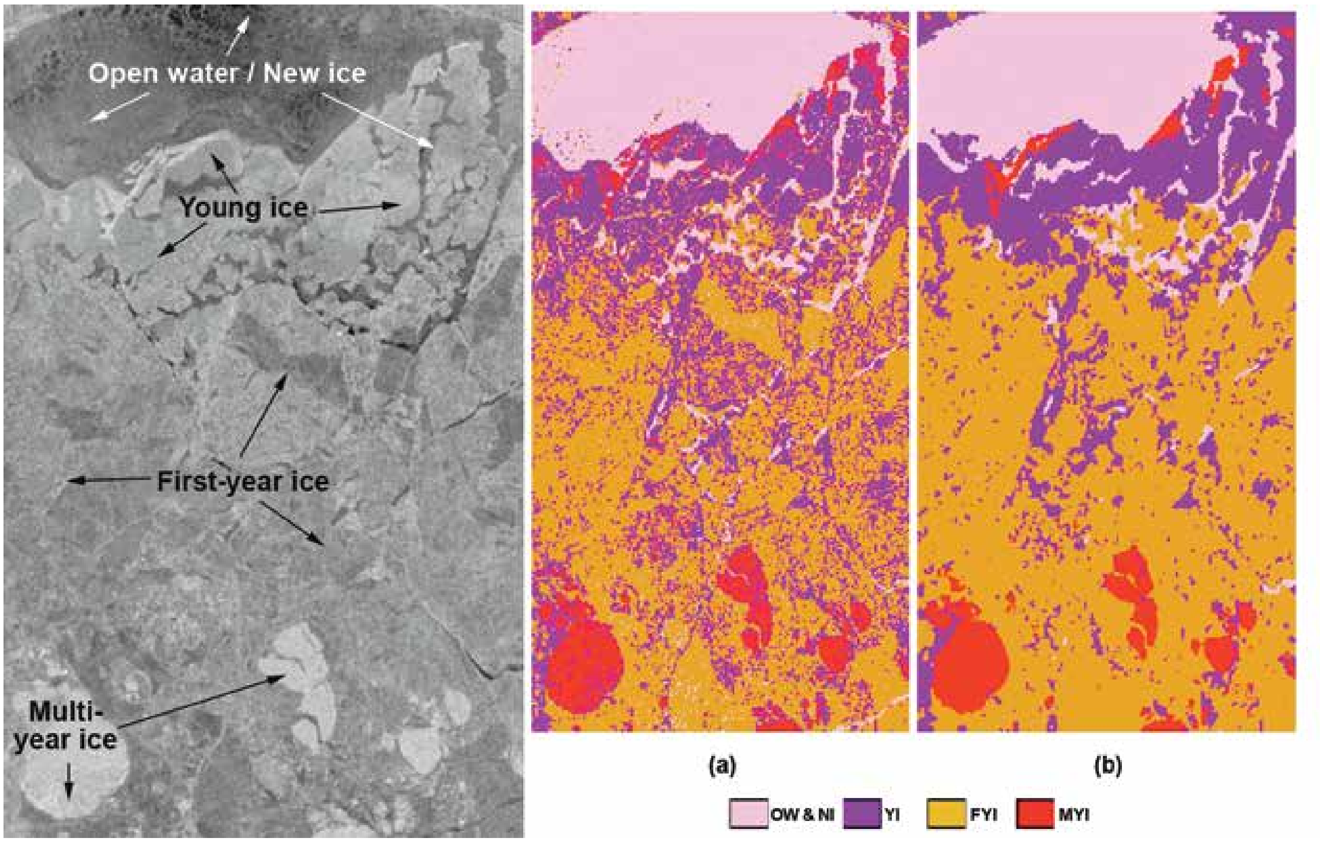

Figure 9. Left – HH representation of full scene depicting various ice types. Middle – "Noisy" classification based on using only an SVM classifier. Right – Improved classification based on IRGS segmentation followed by labelling using CP magnitudes and derived features. This approach generated the highest classification rate when comparing DP features, CP magnitude features, and CP magnitude plus derived features.

dual-pol data. Also, the best classification results are obtained when we use all the CP features in addition to the channel intensity images in the classification scheme. The results indicate that for sea-ice type mapping, CP data is expected to have higher classification success than dual-pol imagery (Figure 9).

Ocean Wave Height Estimation using Compact Polarimetry

We found that the performance of the neural networks was significantly better than the regression models. For the neural network model run on the Radarsat-2 fine-quad beams, we found no effect of incidence angle on the accuracy of the significant wave height estimates. We further found that the two co-pol channels, HH and VV had comparable accuracies, which was unexpected, as VV is generally accepted as more sensitive to ocean surface roughness. We also found that the compact polarimetry channel, RH, had the best performance with slightly higher accuracies than the two co-pol channels (Table 1).

Field Work Results

Average ice thicknesses in the Beaufort Sea were 1.4 m, and between 1.8 and 3.4 m in the high Arctic. Satellite radar data were in good agreement with ice types identified during the surveys. The ice in the Labrador was severely compressed and the ship became beset in thicknesses just over one meter.

Table 1. Summary table for ocean wave height estimates from SAR imagery comparing standard regression with neural networks.

Stepwise Regression								Neural Network							
Experiment	**HH**	**HV**	**VV**	**RH**	**RV**	**RR**	**RL**	**Experiment**	**HH**	**HV**	**VV**	**RH**	**RV**	**RR**	**RL**
correlation coefficient															
1qen, $\Delta\theta = 1$	0.90	0.85	0.82	0.89	0.89	0.77	0.85	1nn, $\Delta\theta = 1$	0.89	0.91	0.85	0.89	0.82	0.81	0.85
1qen, $\Delta\theta = 2$	0.87	0.85	0.83	0.86	0.86	0.80	0.88	1nn, $\Delta\theta = 2$	0.90	0.83	0.89	0.89	0.85	0.78	0.90
2qen, $\Delta\theta = 1$	0.68	0.73	0.62	0.61	0.61	0.71	0.63	2nn, $\Delta\theta = 1$	0.93	0.91	0.88	0.93	0.88	0.84	0.93
2qen, $\Delta\theta = 2$	0.72	0.77	0.65	0.74	0.69	0.79	0.67	2nn, $\Delta\theta = 2$	0.93	0.90	0.92	0.92	0.89	0.85	0.91
1qen(θ)	0.79	0.62	0.69	0.75	0.69	0.68	0.73	1nn(θ)	0.84	0.66	0.80	0.83	0.86	0.64	0.82
2qen(θ)	0.87	0.82	0.83	0.81	0.86	0.74	0.89	2nn(θ)	0.85	0.83	0.69	0.71	0.80	0.76	0.83
RMSE (m)															
1qen, $\Delta\theta = 1$	0.48	0.58	0.54	0.48	0.49	0.61	0.51	1nn, $\Delta\theta = 1$	0.42	0.58	0.48	0.43	0.49	0.58	0.47
1qen, $\Delta\theta = 2$	0.48	0.50	0.51	0.49	0.51	0.54	0.48	1nn, $\Delta\theta = 2$	0.42	0.51	0.47	0.44	0.48	0.59	0.43
2qen, $\Delta\theta = 1$	0.68	0.66	0.71	0.70	0.73	0.65	0.69	2nn, $\Delta\theta = 1$	0.42	0.44	0.47	0.39	0.44	0.52	0.42
2qen, $\Delta\theta = 2$	0.67	0.58	0.67	0.63	0.69	0.59	0.68	2nn, $\Delta\theta = 2$	0.42	0.49	0.42	0.39	0.45	0.50	0.43
1qen(θ)	0.73	0.88	0.79	0.71	0.78	0.86	0.73	1nn(θ)	0.59	0.78	0.71	0.57	0.63	0.85	0.61
2qen(θ)	0.62	0.66	0.59	0.67	0.63	0.78	0.55	2nn(θ)	0.70	0.68	1.02	0.96	0.84	0.69	0.70
Scatter Index (%)															
1qen, $\Delta\theta = 1$	22.84	28.69	27.37	22.95	23.29	30.37	25.09	1nn, $\Delta\theta = 1$	20.01	23.28	22.80	22.05	25.30	27.48	22.19
1qen, $\Delta\theta = 2$	24.87	25.86	27.10	25.58	26.56	27.79	24.95	1nn, $\Delta\theta = 2$	22.53	25.92	23.07	22.35	24.96	29.26	21.56
2qen, $\Delta\theta = 1$	33.25	32.23	34.42	33.38	34.98	31.35	33.41	2nn, $\Delta\theta = 1$	20.51	21.20	21.84	18.64	23.07	26.62	19.07
2qen, $\Delta\theta = 2$	34.08	31.69	35.58	33.10	35.38	30.34	35.94	2nn, $\Delta\theta = 2$	20.70	24.26	20.55	18.83	23.56	26.33	21.23
1qen(θ)	34.92	42.18	41.14	37.46	41.14	41.45	38.50	1nn(θ)	31.55	38.10	35.45	30.23	29.46	42.76	30.39
2qen(θ)	29.16	32.31	29.84	34.21	29.70	39.06	26.03	2nn(θ)	31.74	33.47	47.16	45.53	40.19	34.78	33.65
Standard Deviation of Residuals (m)															
1qen, $\Delta\theta = 1$	0.48	0.58	0.54	0.48	0.49	0.61	0.51	1nn, $\Delta\theta = 1$	0.40	0.47	0.44	0.45	0.51	0.57	0.46
1qen, $\Delta\theta = 2$	0.48	0.49	0.51	0.49	0.51	0.53	0.47	1nn, $\Delta\theta = 2$	0.42	0.50	0.47	0.42	0.48	0.59	0.42
2qen, $\Delta\theta = 1$	0.66	0.66	0.69	0.68	0.71	0.66	0.68	2nn, $\Delta\theta = 1$	0.41	0.44	0.47	0.38	0.44	0.52	0.43
2qen, $\Delta\theta = 2$	0.67	0.56	0.66	0.63	0.67	0.59	0.68	2nn, $\Delta\theta = 2$	0.41	0.49	0.42	0.39	0.45	0.48	0.43
1qen(θ)	0.73	0.88	0.78	0.71	0.78	0.86	0.73	1nn(θ)	0.35	0.60	0.50	0.33	0.39	0.72	0.37
2qen(θ)	0.58	0.63	0.57	0.52	0.64	0.74	0.53	2nn(θ)	0.49	0.45	1.03	0.92	0.70	0.48	0.49
Bias (m)															
1qen, $\Delta\theta = 1$	0.01	0.09	0.08	-0.04	0.03	0.04	0.05	1nn, $\Delta\theta = 1$	0.14	0.13	0.13	0.01	0.01	0.05	0.01
1qen, $\Delta\theta = 2$	0.08	0.09	0.04	0.06	0.03	0.13	0.07	1nn, $\Delta\theta = 2$	0.06	0.11	0.08	0.11	0.05	0.08	0.05
2qen, $\Delta\theta = 1$	0.20	0.04	0.18	0.15	0.17	0.04	0.10	2nn, $\Delta\theta = 1$	0.08	0.08	0.04	0.12	0.01	0.05	0.02
2qen, $\Delta\theta = 2$	0.03	0.18	0.12	0.08	0.15	0.04	0.01	2nn, $\Delta\theta = 2$	0.09	0.05	0.03	0.01	0.01	0.12	-0.04
1qen(θ)	-0.03	-0.02	0.12	0.08	0.10	-0.03	0.09	1nn(θ)	0.02	0.06	-0.04	0.04	0.03	0.01	0.00
2qen(θ)	0.00	-0.06	-0.06	0.02	0.01	0.01	0.07	2nn(θ)	-0.03	0.13	-0.08	0.05	-0.08	0.05	0.02

DISCUSSION

The Canadian Ice Service (CIS) has an active interest in being able to automatically identify sea ice and oil spills in SAR imagery. The use of compact polarimetry (CP) SAR imagery in the next generation of satellites as part of the RADARSAT Constellation Mission (RCM) (Thompson, 2015; Flett et al., 2009) will require new machine learning methods to perform identification of oil and ice in ocean regimes. Our research efforts have led to significant results that have improved on existing techniques for the purposes of automated scene interpretation of SAR imagery applied to northern oceans. 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), on-ice transportation for northern communities, and input into forecasting models.

We have created the first full scene, region-based segmentation and labelling approach designed for CP imagery (Ghanbari et al., 2018) based on the IRGS algorithm (Yu, 2007; Yu, 2008) and glocal approach (Leigh et al., 2014). The region-based approaches are necessary to find homogeneous patches representing unique classes which provides improved feature extraction and more accurate labelling compared to pixel-level approaches. CP provides unique data that can be exploited for classification of full sea ice scenes. We discovered that the CP magnitude-based segmentation improved over dual-pol segmentation, and this agreed with the predictions of CP providing more information than dual-pol. Further, improved labelling performance was generated using CP magnitudes and features relative to CP magnitudes alone or dual-pol magnitudes alone. Previously, we created an IRGS-based segmentation dedicated to quad-pol data using the knowledge that the quad-pol data is governed by the Wishart distribution. Given the success of this approach, we are planning to create a region-based, IRGS algorithm that utilizes CP distributions for full scene segmentation.

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 existing approach based on 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.

We have been able to successfully apply convolutional neural networks (or CNNs, a type of neural network applied for image interpretation problems) to the problem of estimating ice concentration (Wang et al., 2016a; Wang et al., 2016b). These results were demonstrated to be a significant improvement over existing methods. The CNN is able to learn the nature of ice concentration and is then able to estimate ice concentrations automatically from test imagery in a manner that is accurate and visually appealing.

Continuing with the use of recently introduced machine learning algorithms applied to remote sensing scene interpretation, we have been successful applying CNNs to the problem of ice/water classification in SAR scenes (Xu et al., 2018). Our preliminary studies have demonstrated the success of using trained CNNs to generalize the features of ice and water in SAR scenes for subsequent ice/water classification.

Oil spills are rare occurrences in general and there are many lookalikes that can thwart algorithm-based automated detection of true oil spills in SAR imagery. CIS operates a manual system (ISTOP) designed to identify ocean-based oil slicks. 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. We have been successful with a two-step automated approach to solving the problem of automated oil spill detection using SAR imagery. The first step involves identifying candidate oil spills and this is expected to capture all true positives but also a number of false positives. We have developed a conditional random field (CRF) that is able to demarcate a dark spot in SAR ocean imagery to act as a candidate oil spill (Xu et al., 2016a). 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 RCM, and the arduous task of manually searching such data. Our methods for classifying candidate dark spots have been successful (Li et al., 2014; Yin et al., 2015). The synthesis of SAR imagery containing both ice and oil spills is important since real such data is not available and demarcating ice, water, and oil spill is a challenge given the overlapping backscatter characteristics of these classes. Our ice, water, oil spill synthesis algorithm is successful creating such scenes that are realistic that can be used for further algorithm testing (Xu et al., 2016c). We will be extending our methodologies to compact polarimetry by simulating CP via a set of fine quad-pol imagery of the Coal Oil Point seep provided by CIS.

Algorithms used for ice/water classification in oceans have been demonstrated to be successful for the similar problem of ice/water classification in lakes (Wang, et al., 2016). Classification approaches for lake ice types needs to be revisited for further feature extraction and algorithm development as the base methods have not been sufficiently successful in this regard. The advent of CP imagery of lakes will provide an opportunity for improved feature extraction in support of effective lake ice classification. The weakly supervised approaches (Xu et al., 2017) can be used to support the automated labelling of lake ice as we have had success with these approaches for sea ice labelling, following the automated, unsupervised segmentation process.

Results for ocean wave height estimation are significantly better than those reported by Stopa and Mouche (2017), who used Sentinal-1 wave mode data (VV), and trained their neural network models using predictions by a numerical wave model (WaveWatch III), whereas we trained our models directly on buoy observations. Note that Stopa and Mouche (2017) had more than 200000 training samples, while our limited training samples varied with incidence angle between 30 and 100.

The field work associated with this project is part of a long-term initiative, but confirmed that Arctic sea ice thinning continues. While relations with radar backscatter could be established, they are only valid in winter when our measurements took place for logistical and financial reasons, but when few ships sail through the ice.

CONCLUSION

Research to-date has demonstrated an enhanced capability for the identification of ice, oil, and waves in oceans using satellite-based synthetic aperture radar (SAR) imagery. Accurate full scene classifications of sea ice and open water have been achieved and we are now extending this capability to use of compact polarimetry (CP) imagery, in anticipation of the three satellite RADARSAT Constellation Mission to take place later in 2018, and ice typing.

We have created advanced models for the demarcation and labelling of oil spills in SAR imagery. We have shown that compact polarimetry channels with any of the fine resolution beam modes can deliver high resolution estimates of significant wave height, which is particularly important for estimating wave conditions in coastal areas.We will continue dialoguing with the Canadian Ice Service to provide operational algorithms moving forward to the RCM mission.

The field work is significant because it produced unique ice thickness data sets obtained by no other group. Results are used by remote sensing and modeling scientists to develop and validate new algorithms. They are also used by the marine industry to improve strategies to avoid besetting events.

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REFERENCES

Breiman, L. (2001) Random forests. Machine Learning 45 (1): 5–32. doi:10.1023/A:1010933404324.

Brekke, C. and Solberg, A.H.S. (2005) Oil spill detection by satellite remote sensing. Remote Sensing of Environment. Vol. 95, pp. 1-13.

Cao, Y., Xu, L., and Clausi, D.A. (2016a) Active learning for identifying marine oil spills using 10-year RADARSAT data, IGARSS, Bejing, China, July 10-15.

Cao, Y., Xu, L., and Clausi, D.A. (submitted Dec 2016b) Exploring the potential of active learning for automatic identification of marine oil spills using 10-year (2004-2013) RADARSAT data. Submitted to Remote Sensing of Environment.

Charbonneau, F.J., Brisco, B., Raney, R.K., McNairn, H., Liu, C., Vachon, P.W., Shang, J., DeAbreu, R., Champagne, C., Merzouki, A., and Geldsetzer, T. (2010) Compact polarimetry overview and applications assessment, Canadian Journal of Remote Sensing, 36:2, S298-S315, DOI: 10.5589/m10=062.

Clausi, D.A., et al. (2010) MAGIC: MAp-Guided Ice Classification, Canadian Journal of Remote Sensing, 36(S1), pp. S13-S25.

Dabboor, M. and Geldsetzer, T. (2014) Towards sea ice classification using simulated RADARSAT Constellation Mission compact polarimetric SAR imagery. Remote Sensing of Environment, 140, Jan., pp. 189-195.

Decker, V., Budkewitsch, P., and Charbonneau, F. (2014) Natural oil seep detection in Canadian Arctic offshore basins identified from a survey of RADARSAT-2 data and RCM compact polarimetry, IGARSS, Quebec City, July 13-18.

Flett, D. Crevier, Y., and Girard, R. (2009) The RADARSAT Constellation Mission: Meeting the government of Canada's needs and requirements, 2009 IEEE International Geoscience and Remote Sensing Symposium, Cape Town, pp. II-910-II-912.

Ghanbari, M., Xu, L., Jiang, M., and Clausi, D.A. (submitted 2018) Assessment of compact polarimetric SAR imagery for automated sea-ice mapping. Canadian Conference on Computer and Robotic Vision, Toronto, ON.

Hoekstra, M., Duguay, C., and Clausi, D.A. (2016) Automated lake ice/water classification and dual polarization RADARSAT-2 SAR imagery with the iterative region growing using semantics (IRGS) algorithm. American Geophysical Union. Dec 12-16, San Francisco, USA.

Hornafius, J.S., Quigley, D., Lyuendyk, B.P. (1999) The world's most spectacular marine hydrocarbon seeps (Coal Oil Point, Santa Barbara Channel, California): Quantification of emissions. J Geophysical Research:Oceans, 104(C9), 20703-20711.

Laidler, G.J., et al. (2011) Evaluating the floe edge service: How well can SAR imagery address Inuit community concerns around sea ice change and travel safely? The Canadian Geographer, 55, p.91-107.

Leigh, S., Wang, Z., Clausi, D.A. (2014) Automated ice-water classification using dual pol SAR satellite imagery. IEEE Trans. Geosci. Rem. Sens., 52(9), pp. 5529-5539.

Li, Y., Zhang, Y., Chen, J., Zhang, H. (2014) Improved compact polarimetric SAR quad-pol reconstruction algorithm for oil spill detection, IEEE Trans. Geosci. Rem. Sens. Letters 11(6), June, pp. 1139-1142.

Rodriguez, J.J., Kuncheva, L.I., Alonso, C.J. (2006) Rotation Forest: A New Classifier Ensemble Method, IEEE Trans. Pattern Analysis & Machine Intelligence, 28(10), 1619-1630, doi:10.1109/TPAMI.2006.211.

Stopa, J.E., and A. Mouche (2017) Significant wave heights from Sentinel-1 SAR: Validation and applications. J. of Geophysical Research, 122, pp 1827–1848.

Thompson, A.A. (2015) Overview of the RADARSAT Constellation Mission, Canadian Journal of Remote Sensing, 41:5, pp. 401-407.

Wang, J., Duguay, C., and Clausi, D.A. (2016) Great Lakes ice/water classification using dual polarization Sentinel-1A SAR imagery. American Geophysical Union. Dec 12-16, San Francisco, USA.

Wang, L., Scott, K.S., and Clausi, D.A. (2016a) Improved sea ice concentration estimation through fusing classified SAR imagery and AMRS-E data. Canadian Journal of Remote Sensing. 42(1), pp. 41-52, DOI: 10.1080/07038992.2016.1152547.

Wang, L., Scott, K.A., Xu, L., Clausi, D.A. (2016b) Sea ice concentration estimation during melt from dual-polarized SAR images using deep convolutional networks: A case study. IEEE Trans. Geosci. Rem. Sens., 54(8), pp. 4524-4533.

Wang, L., Scott, K.A., Clausi, D.A. (2016c) "Estimating ice concentration from SAR images using a convolutional neural network", presented at the 17th meeting of the Sea Ice Modelling Working Group, Dec 1-2, Montreal, Canada.

Xu, L., Shafiee, M.J., Wong, A., Clausi, D.A. (2016a) Fully-connected continuous conditional random field with stochastic cliques for dark-spot detection in SAR imagery. J-STARS, 9(7), 2882-2890.

Xu, L. Clausi, D.A. (2016b) Deep convolutional neural network for ice-water classification using dual-pol Sentinel-1 imagery. ArcticNet Annual Scientific Meeting, Winnipeg, MB, Dec 5-9.

Xu, L., Wong, A., Clausi, D.A. (2016c) An enhanced probabilistic posterior sampling approach for synthesizing SAR imagery with sea ice and oil spills. IEEE Geosci and Rem. Sens. Letters, 14(2), pp. 188-192.

Xu, L., Clausi, D.A., Li, F., and Wong, A. (2017) Weakly-supervised classification of remotely sensed imagery using label constraint and edge penalty. IEEE Trans. Geosci. Rem. Sens., 55(3), pp. 1424-1436.

Xu, L., Clausi, D.A., Wong, A. (submitted March 2018) The classification of sea-ice and open water from Sentinel-1 imagery using a deep convolutional neural network approach. Remote Sensing of Environment.

Yin, J., Moon, Moon, W., and Yang, J. (2015) Model-based pseudo-quad-pol reconstruction from compact polarimetry and its application to oil-spill observation. Journal of Sensors, Article ID 734848, 8 pages.

Yu, Q. and Clausi, D.A. (2007) SAR sea-ice image analysis based on iterative region growing using semantics, IEEE Trans. Geosci. Rem. Sens., 45(12), Part I, 3919-3931.

Yu, Q. and Clausi, D.A. (2008) IRGS: MRF based image segmentation using edge penalties and region growing. IEEE Trans. PAMI, 30(12), 2126-2139.

PUBLICATIONS

Beckers, J.F., (2017), Altimeter Retrievals of Sea Ice, Lake Ice and Snow Properties, PhD Thesis, University of Alberta, 253 pp.

Hoekstra, M., Duguay, C., and Clausi, D.A. (2017) Automated ice-water classification on large northern lakes using RADARSAT-2 SAR imagery. Poster presented at EO Summit. June 20-22, Montreal, QC.

L. Wang, K.A. Scott and D.A. Clausi (2017) Ice concentration estimation in the Gulf of Saint Lawrence using a fully convolutional neural network, IEEE Geoscience and Remote Sensing Symposium, Fort Worth, USA, July 23-28, 2017, 4 pages.

Wang, J., Duguay, C., Clausi, D.A., Jiang, M., and Stone, M. (2017) Lake Erie ice classification using dual polarization RADARSAT-2 imagery. Poster presented at EO Summit. June 20-22, Montreal, QC.

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

Project Team

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ABSTRACT

ArcticNet Long-Term Oceanic Observatories (LTOO) have been deployed in the Canadian Arctic since 2002. LTOO, or oceanographic moorings, are lines anchored to the seafloor onto which recording instruments are deployed at different depths. These instruments record current speed and direction, salinity, temperature, nutrients, chlorophyll, and ambient noise, including marine mammal vocalizations. Some moorings also carry sediment traps, which are large automated funnels that collect particles sinking from the surface layer of the ocean to the seafloor at regular intervals. Such particles include ice algae, phytoplankton, zooplankton fecal pellets and all sorts of detritus, which are excellent indicators of the intensity of the processes taking place at the ocean surface at times when sampling by ship is not possible. Moorings are deployed and recovered every year, and as years accumulate, the time-series of sinking particles collected by the sediment traps will reflect any long-term change in the ecosystem associated with shifts in temperature, salinity, or sea ice regime. The objective of the last phase of the ArcticNet-LTOO project is to assess variations in the 16-year record to detect any response of the ecosystem to recent physical changes and the expected modifications in the services provided to local communities.

KEY MESSAGES

- Warmer water temperatures following the record sea-ice minimum of 2012 combined to a late sea-ice break-up in 2013 led to a mismatch between primary and secondary producers in the Beaufort Sea.
- Primary production and export fluxes of biogenic matter were as high during fall 2015 at a time of open water and high storm frequency than during summer 2016 on the shallow Chukchi Sea shelf.
- Dinoflagellates cyst fluxes collected from September 2014 to August 2015 were very limited or absent during ice-covered periods at the Beaufort Sea shelf break. The timing of individual species production varied from one region to another.
- The low-frequency under-ice ambient noise in Amundsen Gulf increased by up to 7 dB from 2006 to 2016, likely in response to the increase in ice movement associated with climate change.
- Earlier ice melt in 2016 than in 2015 resulted in earlier and higher export of diatoms but lower fluxes of the ice algae *Nitzschia frigida* at the Beaufort Sea shelf break.
- Peaks in diatom export fluxes were observed at the onset of snow and ice melt in May and June 2006 in northern Baffin Bay, several weeks before the usual sampling of the northern Baffin Bay transect on board the CCGS *Amundsen*.

RESEARCH OBJECTIVES

The objectives for Phase 4 of the ArcticNet LTOO project were:

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

As proposed, mooring deployments were continued in the Beaufort Sea and expanded to international waters during the last phase of the LTOO project. In the Beaufort Sea, moorings CA05 and CA08 were redeployed in partnership with the integrated Beaufort Observatory (iBO) funded by the Environmental Studies Research Funds (ESRF) and led by ArcticNet and IMG-Golder. In the western Arctic Ocean, a sediment trap was added to the existing Chukchi Ecosystem Observatory (CEO) oceanographic mooring deployed on the northern Chukchi continental shelf and managed by the Alaska Ocean Observing System (AOOS). In the Canadian Arctic Archipelago, an oceanographic mooring carrying a sediment trap was deployed in the Queen Maud Gulf as part of the Kitikmeot Marine Ecosystems Study regrouping partners from the W. Garfield Weston Foundation, Parks Canada, Québec-Océan and ArcticNet. The long-term physical, biological, and biogeochemical datasets obtained from these recent mooring deployments and from those deployed during the previous phases of ArcticNet are invaluable.

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 Mackenzie Shelf and in Amundsen Gulf in the Beaufort Sea. As proposed, a synthesis of the 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 concentrations from 2002 to 2018 was undertaken. In addition to total particulate matter

(TPM) and particulate organic carbon (POC) fluxes already available for all deployments before 2014-2015, microscopic analyses were conducted on recent and historic samples for the investigation of decadal variations in the nature of the exported material as a proxy for change in ecosystem function.

Taxonomic analyses of zooplankton (swimmers) collected in sediment traps were also undertaken for deployments during Phase 4.

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

As proposed, short moorings were deployed in northern Baffin Bay in support of the development of a state-of-the-art high-resolution coupled ice-ocean numerical model covering the entire Baffin Bay, from Davis Strait to the Lincoln Sea.

INTRODUCTION

The high seasonality in sunlight, snow, ice cover, and water temperature restricts the biologically productive season of the Arctic marginal seas to a few months during spring and summer. In these seasonally ice-covered seas, snow melt triggers the sloughing of ice algae and the onset of pelagic microalgal production by regulating the amount of light reaching the underside of the ice and the upper water column (Welch and Bergmann, 1989; Cota et al., 1991; Fortier et al., 2002). This relatively short production period during spring and summer shapes the lipid-based Arctic food web and leads to large populations of fish, seabirds and marine mammals (Falk-Petersen et al., 2009; Darnis et al., 2012). The *Calanus* copepods dominate the herbivore pelagic community in terms of biomass (Hopcroft et al., 2005; Kosobokova and Hopcroft, 2010; Darnis et al., 2012) and play a pivotal role in the lipid-based Arctic food web by transforming low-energy lipids from phytoplankton into high-energy long lipid chains available for higher trophic levels (Falk-Petersen et al., 2007; Falk-Petersen et al., 2009; Darnis et al., 2012; McBride et al., 2014). This crucial energy flow is dependent on a tight coupling (match) between production of both ice and pelagic diatoms and the vernal vertical migration of the *Calanus* copepods (Søreide et al., 2010; Wold et al., 2011; Ji et al., 2013).

Climate warming is causing a rapid reduction in ice cover extent and thickness and rise in surface and intermediate water temperature in the Arctic Ocean (Polyakov et al., 2010; IPCC, 2014; Richter-Menge et al., 2016). These physical changes have the potential to impact the timing of ice algae release, microalgae production, and copepod migration, and therefore the match between primary and secondary producers and the subsequent transfer of energy within the Arctic food web (Kiørboe, 1991; Falk-Petersen et al., 2009; Søreide et al., 2010; Leu et al., 2011). In this rapidly changing context, long-term observations are needed to monitor the response of Arctic marine ecosystems to climate warming. Continuous multi-annual observations are however scarce, as ship-based observations in the Arctic regions are limited to the short minimum sea-ice extent season, typically ranging from July to October. As an alternative, sediment traps deployed on moorings have proven useful to collect biological samples such as microalgae and zooplankton on an annual scale in several remote areas of the Arctic Ocean (Forbes et al., 1992; Gislason and Astthorsson, 1992; Seiler and Brandt, 1997; Zernova et al., 2000; Willis et al., 2006; Willis et al., 2008; Kraft et al., 2010; Makabe et al., 2010; Kraft et al., 2012; Lalande et al., 2014; Matsuno et al., 2015; Onodera et al., 2015; Lalande et al., 2016).

Moored sediment traps have been deployed since 2002 in the Beaufort Sea as part of the Long-Term Oceanic Observatories project funded by the ArcticNet Network of Centres of Excellence of Canada to study variations in the physical, biological and biogeochemical properties of the region. The establishment of the observatories coincided with the recent loss of multiyear ice and prolongation of the open-water period in the Beaufort Sea (Galley et al., 2016). Such sea ice loss may lead to a significant increase in primary production (Arrigo et al., 2008; Jin et al., 2012), while the longer open-water period has the potential to result in more frequent autumn blooms due to additional nutrient input induced by wind mixing (Ardyna et al., 2014). To better assess the impact of these severe changes in physical conditions on the marine ecosystem, microalgae and zooplankton collected with sediment traps at the Beaufort Sea shelf break were analysed over a 7-year period from September 2009 to September 2016 (no data from September 2013 to August 2014). Seasonal and interannual variations in microalgae export and in migration patterns of the herbivorous *Calanus* copepods were monitored in relation to changes in sea ice concentration, snow cover, and hydrographical conditions.

ACTIVITIES

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

- Three moorings carrying six sediment traps were recovered jointly by ArcticNet-LTOO and the iBO initiative in the Beaufort Sea on board the CCGS *Laurier* in September 2017. Two LTOO-dedicated moorings (CA05 and CA08) carrying two sediment traps were not recovered due to technical issues with the acoustic releasers. Moorings CA05 and CA08 were nonetheless redeployed along with the other iBO moorings for a 2017-2018 deployment. Out of the six sediment traps recovered, two sediment traps did not rotate properly and did not provide samples. A mooring engineer (Gregg Curtis) coordinated the recovery, calibration and redeployment of moored instruments on board the CCGS *Laurier*.
- The Chukchi Ecosystem Observatory mooring deployed on the northern Chukchi shelf was successfully recovered on board RV *Norseman II* in August 2017. The sequential sediment trap had a technical problem and samples collected were unusable. The trap was not redeployed on the mooring and was sent back to the manufacturer in Germany for reparation. A Research Associate (Catherine Lalande) participated as technical support for mooring recovery and redeployment on board the RV *Norseman II*.
- The Kitikmeot Marine Ecosystems Study mooring was successfully recovered and redeployed on board the CCGS *Amundsen*. Sediment trap samples are currently being processed. Thibaud Dezutter was hired as a Research Associate (LTOO=30%) to work on sediment trap analyses.

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 and Queen Maud Gulf in 2017 are underway at Université Laval. Microscopic identification of phytoplankton cells and CHN analyses are completed. Removal and identification of swimmers are ongoing and will be completed in the coming weeks.
- Thibaud Dezutter completed his M.Sc. thesis entitled '*Réchauffement et 'match-mismatch' entre le phytoplancton et le zooplankton dans la mer de Beaufort*' in June 2017. The associated scientific paper *Match-mismatch between phytoplankton and zooplankton in the Beaufort Sea is* in preparation and will be submitted to the journal Global Change Biology.
- Microscopic identification of phytoplankton cells collected in sediment trap samples deployed during the previous LTOO phases are still ongoing as part of the long-term monitoring of the pelagic ecosystem function in the Beaufort Sea. At the moment, ~50% of the microscopic analyses on historic samples available have been completed.
- Gabrielle Nadaï received a M.Sc. NSERC grant to study the *Impact of early sea ice retreat on phytoplankton export in the Beaufort Sea* as a contribution to LTOO. She started her M.Sc. in

September 2017 and completed her Seminar I in November 2017. She will complete a course on Arctic phytoplankton in May 2018 at the University Centre in Svalbard (UNIS).

- Dinoflagellate cyst flux results obtained at the Beaufort Sea shelf break in 2014-2015 in collaboration with Vera Pospelova at the University of Victoria were presented at the 11th International Conference on Modern and Fossil Dinoflagellates and will be submitted in a manuscript in the coming months.
- All LTOO observations of *Polarella glacialis*, a dinoflagellate species that forms a resting stage that appears to be fossilizable, were compiled to contribute to a scientific article on the large-scale distribution and seasonal production of *P. glacialis* cysts in the Arctic Ocean to explore its potential as an Arctic paleo-sea ice proxy. This project is led by Sofia Ribeiro at the Geological Survey of Denmark and Greenland in Copenhagen and is conducted in collaboration with the Arctic Science Partnership (Søren Rysgaard), the Greenland Ecosystem Monitoring Programme (Mikael Sejr), and Takuvik (Guillaume Massé).
- Thibaud Dezutter, Catherine Lalande, Gabrielle Nadaï, Marie Parenteau and Vera Pospelova presented results obtained as part of the LTOO project at various meetings and conferences.

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

- Two moorings measuring hydrographic water properties and current velocities in northern Baffin Bay were successfully recovered and redeployed in 2017.

RESULTS

The following section includes results obtained during the final (2015-2018) and previous phases of the LTOO project that are in preparation for publication.

Match-mismatch between phytoplankton and zooplankton in the Beaufort Sea (Dezutter, Lalande, Dufresne, Darnis, Fortier)

The unprecedented pace of warming of the Arctic Ocean affects a wide range of pelagic processes, from primary production to fish recruitment. Sequential sediment traps deployed on oceanographic moorings at the Beaufort Sea shelf break were used to investigate the impact of variations in physical conditions on the phenology of microalgae and herbivorous copepods. Water temperature, salinity, microalgal fluxes, and zooplankton fluxes were monitored over 6 of the 7 annual cycles from September 2009 to September 2016 with a hiatus from September 2013 to August 2014. Satellite-derived sea ice concentration and modeled snow depth were retrieved for the same period. For 5 of the 6 cycles, vernal abundance of *Calanus glacialis nauplii* and *Calanus hyperboreus* copepodites were synchronized with peaks in diatom export, while the vernal migration of *Calanus glacialis* preceded peaks in the export of the ice alga *Nitzschia frigida* by 6 to 8 weeks. Following the record sea-ice minimum of 2012, warmer upper water temperature during autumn and winter 2012-2013 combined to a late sea-ice break-up in 2013 induced a disruption of the usual flux patterns and to a mismatch between primary and secondary producers in the Beaufort Sea. Unusually warm winter water temperature in the polar mixed layer and Pacific halocline led to a shoaling of the vertical distribution of *C. hyperboreus* females and their *nauplii* above 125 m from February to April 2013 instead of the normal deep winter distribution. The late snow and ice melt of 2013 delayed ice algae export, resulting in a mismatch between *C. glacialis* females and *N. frigida* fluxes and in a reduction of entrapped *C. glacialis nauplii* in June and July 2013 compared to other years sampled. These mismatch events likely had a negative impact on *Calanus* recruitment and on the subsequent transfer of energy to carnivorous zooplankton, fish, and seabirds. As unpredictable sea ice conditions occur more frequently and water temperature increases, such mismatch events between microalgae and zooplankton are likely to become more frequent.

Impact of early sea ice retreat on phytoplankton export in the Beaufort Sea (Nadaï, Lalande, Parenteau, Fortier)

Recent satellite-derived observations suggest that the current reduction in sea ice cover extent and thickness resulted in increased primary production during spring and/or fall on several Arctic continental shelves. However, satellites are unable to detect primary production under ice, clouds or deeper than 10 m in the water column. Ship-based observations in the Arctic Ocean are also incomplete, as they are usually limited to a restricted area and to the period of minimum ice extent. As part of ArcticNet's Long-Term Oceanic Observatories (LTOO) project, moored sediment traps were re-deployed over several years in the Beaufort Sea. Sediment traps provide continuous and sequential biological samples at a high temporal resolution over an annual cycle, tracking spatial, seasonal and interannual variations in the pelagic ecosystem. In this study, phytoplankton cells collected in sediment traps were quantified and identified to investigate changes in abundance and composition associated with variations in the sea ice regime and water temperature. Preliminary results from a sediment trap deployed at the Beaufort Sea shelf break from September 2014 to September 2016 showed that an earlier ice melt in 2016 than in 2015 resulted in earlier and higher export of diatoms, but in lower fluxes of the ice alga *Nitzschia frigida*. Analyses are ongoing to further investigate trends between ice regime, water temperature and phytoplankton export at other sites and for additional years.

Succession of phytoplankton species in northern Baffin Bay (Lalande, Parenteau, Fortier)

The northern region of Baffin Bay has been sampled nearly every year since 2005 as part of the annual ArcticNet expeditions on board the CCGS *Amundsen*. Apart from 2014 when sampling took place at the end of July, sampling at the northern Baffin Bay transect usually occurred in August, September, and more frequently in October, several weeks after most of the phytoplankton production has occurred. One approach to palliate this want of information on pelagic production over an annual cycle is to record the export flux of particles with sediment traps. As part of the ArcticNet's Long-Term Oceanic Observatories project, two sequential sediment traps were moored in northern Baffin Bay from August 2005 to August 2006. Taxonomic analyses were conducted on these sediment trap samples to quantify phytoplankton fluxes and determine the succession of species, particularly at the onset of the productive season. In this study, we present seasonal variations in key diatom species (*Nitzschia frigida* and *Melosira arctica*) and in less abundant groups (small flagellates, dinoflagellates, and ciliates) to monitor the succession of species in relation to snow and ice melt in the region. This monitoring of algal cell fluxes provides a better comprehension of the spatial and temporal variation in primary production in northern Baffin Bay.

Annual cycle of biogenic matter exported on the Chukchi Sea continental shelf: 2015-2016 (Lalande, Grebmeier, Fortier, Danielson)

The Chukchi Ecosystem Observatory (CEO) is designed to autonomously record year-round high-resolution data representing multiple disciplines and trophic levels in the northeast Chukchi Sea. Since August 2015, a sequential sediment trap has been deployed annually as part of the CEO to assess the seasonal and interannual variations in the export of biogenic matter reflecting pelagic production on the shallow (45 m) Chukchi continental shelf. Export fluxes of chlorophyll a (chl a), phytoplankton cells, zooplankton fecal pellets, particulate organic carbon (POC) and total particulate matter (TPM) were measured at 37 m at a 1-month resolution during winter and at a 1-week resolution during spring. Zooplankton actively entering and dying in the sediment trap (swimmers) were also identified and quantified to provide insight on the seasonal patterns of zooplankton development and migrations. Export fluxes obtained from August 2015 to July 2016 clearly showed two very large peaks (fall and summer) in chl a and phytoplankton export, with diatoms representing >93% of phytoplankton cells collected at all times. Elevated chl a and diatom fluxes were observed in September and October 2015 at a time of high storm frequency and open water in the area. Diatom cells exported during fall were nearly all *Cylindrotheca closterium*, a benthic-planktonic diatom found in shallow waters that grows rapidly when transported upward into the water column during and following mixing events. Diatom fluxes remained low from November to May, but were still relatively high compared to diatom fluxes recorded on other Arctic shelves. Two peaks in fluxes of the ice algae *Nitzschia frigida* were observed in May and June-July, indicating at least two snow melt events before ice retreated from the region as ice algae are released from the ice when snow melt is initiated. Chl a and diatom fluxes 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 and subsequently redeployed. Diatom fluxes were as high during fall 2015 as during summer 2016, underscoring the tremendous importance of fall blooms for the annual primary production of the Chukchi Sea. Similar to chl a and diatoms, POC fluxes were also high in September and October and in June and July, but still displayed considerable export at other times during deployment, matching with TPM fluxes and probably reflecting resuspension events on the shallow shelf.

Earlier algal export under thinner ice cover in the Eurasian Arctic Ocean (Lalande, Nöthig, Fortier)

Satellite-derived observations suggested a recent increase in annual primary productivity in the Eurasian sector of the Arctic Ocean following considerable loss of summer sea ice. The scarcity of field data to corroborate these satellite estimates incited a collaborative international project combining six years of sequential sediment trap measurements obtained over a 17-year period in the Eurasian Arctic Ocean. Here we present algal fluxes measured continuously at ~200 m over the Eurasian shelf break and basins. Whereas the intensity of algal release remained similar over the 17-year period, the earlier release of ice algae observed was likely triggered by earlier snow melt. These long-term algal fluxes reflect the continuously important contribution of ice algae at several locations in the Eurasian Arctic Ocean and suggest that satellite-derived trends are unreliable for this region.

Dinoflagellate cyst production in the presence/absence of sea ice cover in the Beaufort Sea (Arctic Ocean): one year sediment trap record (Pospelova, Lalande, Heikkilä, Fortier)

Studies of dinoflagellate cyst time series in sediment traps provide essential information on weekly, monthly, seasonal, annual, and/or multi-annual changes in cyst fluxes in relation to measured or implied environmental parameters. Such information is essential for understanding ecological preferences of individual cyst taxa which is the foundation for performing reliable (paleo)environmental high-resolution regional reconstructions. Up to date, sediment trap studies are rare, and only three of those deal with dinoflagellate cysts production in ice-covered conditions: in Antarctic waters (Harland and Pudsey, 1999); Arctic fjords in the Svalbard archipelago (Howe et al., 2010); and Hudson Bay (Heikkilä et al., 2016). All these studies consistently show a very limited or no cyst recovery from the samples that were collected during the ice-covered intervals. However, the timing of individual species production (e.g. cysts of *Pentapharsodinium dalei*, *Islandinium minutum*, and *Spiniferites elongatus*) within the ice-free condition is inconsistent as it varies from region to region.

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.

Decadal change in under-ice ambient noise in the Eastern Beaufort Sea, Canadian Arctic (Kinda, Simard, Gervaise, Fortier)

The 2015-2016 time-series of acoustic recordings at the LTOO mooring CA08 was analyzed for ambient underwater noise and compared with the similar year-round series acquired 10 years before (Kinda et al., 2013). As for 2005-2006, the analysis of the natural forcing (wind, wave, ice cover, ice movement) showed strong correlations of the ambient noise annual series with the presence of an ice cover, the ice thickness, and the large-scale movement of the ice, notably the multi-year ice plume in Eastern Beaufort Sea. The low-frequency under-ice ambient noise in Amundsen Gulf in 2016 increased by up to 7 dB depending of the frequency compared to 2006, likely in response to the increase of ice movement associated with climate change. This large increase in low-frequency ambient noise is equivalent to that resulting from two decades of shipping noise increase at the lower latitudes where global shipping is concentrated. These preliminary results have been presented at the following forums.

Annual cycle of phytoplankton and zooplankton in the Queen Maud Gulf region (Dezutter, Lalande, Fortier)

The recent discovery of Franklin's ship HMS *Erebus* in eastern Queen Maud Gulf led to a burst of scientific interest for the Kitikmeot region. As part of the Kitikmeot Marine Ecosystems Study, a partnership with Parks Canada jointly funded by the W. Garfield Weston Foundation and ArcticNet, a moored sediment trap has been re-deployed in Queen Maud Gulf starting in October 2015 to better understand the dynamics of the marine ecosystem of the region. Here, seasonal variations in phytoplankton (ice alga *Nitzschia frigida* and diatoms) and zooplankton (*Calanus hyperboreus*, *Calanus glacialis, PseudoCalanus spp., Metridia longa* and *MicroCalanus spp.*) collected in sediment trap samples from October 2015 to September 2016 are presented to investigate the timing and magnitude of primary production and secondary production in relation to sea ice in the region. Sea ice remained above the mooring until mid-July, providing favorable conditions for the growth of *N. frigida* late into the summer. The ice breakup led to maximum diatom export in early June. Peaks in the occurrence of the herbivorous copepods *C. glacialis* and *PseudoCalanus spp.* in the traps were observed a few weeks before the export of *N. frigida*. These results confirm that *C. glacialis* and *PseudoCalanus spp*. use ice algae to fuel their reproduction and a match between copepod *nauplii* and the following elevated diatom fluxes in June. Overall, sediment trap samples showed a clear ontogenic succession through the year of the omnivorous copepods *M. longa* and *MicroCalanus spp.* and the herbivorous *PseudoCalanus spp*., *C. hyperboreus* and *C. glacialis.* The Queen Maud Gulf marine ecosystem is still strongly influenced by ice and ice algae compared to other Arctic regions.

DISCUSSION

A 6-year assessment of export fluxes at the Beaufort Sea shelf break indicated that while five of the years sampled reflected a temporal match between microalgae and herbivorous copepods, the reduced ice conditions and warmer water temperatures in 2012 followed by heavy ice conditions in 2013 led to a mismatch in 2013. Below we discuss the impact of the longer open water period of 2012 and heavy ice and snow conditions of 2013 on phytoplankton and zooplankton, and the effect of their mismatch on the marine ecosystem of the Beaufort Sea.

The reduced sea ice extent combined with loss of multiyear ice and prolongation of the open-water period recorded in the Beaufort Sea since 2004 have led to longer exposition of surface waters to wind stress (Galley et al., 2016). Such conditions enhance wind-driven vertical mixing of the water column late in the season which has the potential to result in more frequent autumn blooms due to additional nutrient input, as recently observed in several Arctic regions (Ardyna et al., 2014; Meier et al., 2014). Over the Beaufort Sea shelf break, enhanced diatom fluxes of ~1 million cells m^{-2} d^{-1} recorded during late autumn in 2010, 2012 and 2014 reflected relatively high phytoplankton production. Those events coincided with late sea ice formation and reversed current directions in the upper 200 m of the water column in early November, likely reflecting the formation of upwelling or eddies in the area (Carmack, 2003; Tremblay et al., 2008). These events potentially replenished nutrients into the upper water column, initiating primary production and leading to enhanced export of diatoms, with cells containing chloroplasts (12-30 %) indicating recent and local production. During the record of low sea-ice extent of 2012, the area remained free of ice until mid-November, allowing for a longer period of wind-induced water mixing and resulting in an exceptionally long autumn production with diatom fluxes observed until February 2013.

Reduced ice extent also affects the timing of ice algae release and phytoplankton production in spring. Early blooms due to precocious ice break-up were documented in several regions of the Arctic Ocean based on remote sensing measurements (Kahru et al., 2011) and predicted by models in the Beaufort Sea (Lavoie et al., 2010). Sediment trap results over the Beaufort Sea shelf break also indicated progressively earlier peaks of diatom fluxes during spring, with peak flux observations advancing from August in 2011 to May in 2016 (no data in 2014).

The Beaufort Sea became ice-free for the first time during the observational record in September 2012. The longer open water period that year led to positive anomalies in solar absorption from May to October (Babb et al., 2016). This increase in solar absorption resulted in significantly warmer water temperatures recorded at ~50 m at the Beaufort Sea shelf break from November 2012 to June 2013. Increased current velocities and reversal of wind and current directions in October and November 2012 (data not shown) have likely contributed to trap the warm surface water under the halocline during the following winter, as previously observed in the Canada Basin (Jackson et al., 2010).

In the Beaufort Sea, *Calanus hyperboreus* copepodites C3 to adult usually overwinter in the relatively warm (>0°C) Atlantic layer below 200 m and migrate upward the following spring ready to feed on the ice algae and phytoplankton cells in the surface layer (Ashjian et al., 2003; Darnis and Fortier, 2014). Warmer water temperature (+ 0.6°C) during winter 2013 likely allowed *C. hyperboreus* F to range into shallower depths than usual, as indicated by the high numbers of individuals (up to 24 m^{-2} d^{-1}) collected at ~100 m from January to March 2013 in contrast to ≤7 ind. m^{-2} d^{-1} in the other years sampled. In the Canadian Beaufort Sea, *C. hyperboreus* generally reproduces between January and April at depth (Ota et al., 2008; Darnis et al., submitted). The large quantity of *C. hyperboreus* young *nauplii* (~180 m^{-2} d^{-1}) observed at ~100 m in February-March 2013 supports the assumption that females spawned at depths around trap long before ice algae and phytoplankton cells started to grow. Pattern of abundances of females and *nauplii* in the trap at 125 m in winter 2013 are comparable to those observed by Ota et al. (2008) in traps at 200 m in the shallower Amundsen Gulf during winter 2004. The 2003-2004 annual cycle was characterized by an ice buildup in October typical for the region and a Pacific Halocline layer with subzero temperature values like the other years of our time series (Forest et al. 2008). Thus, the similar pattern of abundance of females and *nauplii* in traps at two different depths in January-March 2004 and 2013, respectively, backs the assumption that warmer Pacific Halocline in winter 2013 extended the vertical range of females during their season of reproduction. This pattern was not observed for the other overwintering stages C3-C5 that were poorly represented in the winter trap samples.

The record minimum ice cover of September 2012 was followed by an anomalous ice growth in 2013, likely due to a combination of factors including ice dynamics, oceanic and atmospheric heat transport, wind, solar insolation anomalies and negative cloud forcing anomalies (Liu and Key, 2014). Drift of this ice led to summertime ice concentration anomalies over the Beaufort Sea, explaining the late ice break-up observed in August 2013 in the region above the mooring at the Beaufort Sea shelf break.

While most Arctic diatom species thrive both in ice and water, the pennate diatom *Nitzschia frigida* is exclusively sympagic and reliably indicates the onset of ice algae release from the ice (Von Quillfeldt, 1997; Von Quillfeldt et al., 2003; Poulin et al., 2011). *N. frigida* was consistently among the first diatom species exported and displayed a single export peak for every year sampled. As expected, the export of *N. frigida* coincided with the onset of snow melt (Welch and Bergmann, 1989; Cota et al., 1991; Fortier et al., 2002), and the late snow melt in 2013 delayed the export of *N. frigida* until the end of June. While the peak in diatom export always occurred after the export of *N. frigida*, the late snow melt in 2013 led to the simultaneous export of sympagic and pelagic diatoms while ice was still present in the region. Indeed, the totality of phytoplankton export occurred under ice following snow melt at a time of high irradiance in June. The under-ice bloom was triggered due to snow and ice melt, reflected by a pulse of fresher water at ~50 m in June and July.

In the Canadian Beaufort Sea, *C. glacialis* exploits both ice algae and pelagic phytoplankton to reproduce and develop (Daase et al., 2013). Females migrate toward the surface before or at the onset of ice algae production to fuel their maturation and egg production (Søreide et al., 2010; Leu et al., 2011), while the first feeding stage N3 offspring feed on the ensuing pelagic primary production to fuel growth and development (Tourangeau and Runge, 1991; Søreide et al., 2010; Wold et al., 2011). For 5 of the 6 years sampled, the upward migration of *C. glacialis* F preceded the export of *N. frigida* by 6 to 8 weeks, reflecting a match between the start of the ice algae production and *C. glacialis* F reaching the surface. In 2013, the upward migration of *C. glacialis* F preceded the export of *N. frigida* by 13 to 15 weeks due to the late snow melt, causing a mismatch between F and ice algae production and release. In addition, the delayed export of *N. frigida* resulted in an overlap with the export of pelagic diatoms, supressing the gap usually exploited by *C. glacialis* for their *nauplii* to develop from lipid reserves into first feeding stage N3 at the time of pelagic production (Daase et al., 2013). The lowest *nauplii* abundance observed in the following weeks from June to August 2013 strongly suggests reduced *C. glacialis* recruitment due to this mismatch. Leu et al. (2011) observed a similar situation in a seasonally ice-covered fjord in Svalbard when a late sea ice break-up reduced the period between ice algal and pelagic production, resulting in a lower abundance and biomass of *C. glacialis* that summer.

The persistent ice cover in 2013 would have also negatively impacted *C. hyperboreus* recruitment. Buoyant *C. hyperboreus* eggs develop into the *nauplii* first feeding stage N3 while floating, reaching surface waters before or at the onset of the pelagic production (Conover and Huntley, 1991; Melle and Skjoldal, 1998; Ringuette et al., 2002; Jung-Madsen et al., 2013). As successful recruitment depends on a match between *nauplii* development and phytoplankton bloom (Ringuette et al., 2002; Daase et al., 2011), *nauplii* that hatched at shallower depths in March 2013 were likely to starve as the peak in *nauplii* abundance occurred 12 to 14 weeks before the peak in diatom export. *Calanus nauplii* N1 dominated largely in the trap samples at that period (data not shown). A calculation of development time using a Belehrádek's function (Ji et al., 2012) with a temperature range of -1 -1.7 °C for the uppermost layer above the trap, indicates that the *nauplii* NI found in March would have taken between 13 and 15 days to develop to N3, the first developmental stage to be limited by food availability. Thus, the N3 did go through a period of starvation of at least 10 weeks in 2013 before the first ice algae and phytoplankton cells were collected by the trap. Incubation experiments have shown that N3 are able to withstand starvation for at least one month (Jung-Madsen et al., 2013). However, it is unlikely that they have sufficient reserves to last more than twice that time without food. The increased starvation time in 2013 must have enhanced *nauplii* mortality and affected recruitment to the copepodite stages later in the season.

CONCLUSION

As herbivorous copepods *C. hyperboreus* and *C. glacialis* constitute an important food source for polar cod, and copepod *nauplii* are the preferred prey of polar cod larvae (Michaud et al., 1996; Benoit et al., 2010), a lower abundance of *Calanus nauplii* and copepodites in 2013 potentially reduced juvenile and adult polar cod abundance and biomass. Indeed, a five-year temporal series of acoustic data obtained from ship mounted Simrad echosounder and epipelagic net samples obtained from late summers 2010 to 2014 in the Beaufort Sea showed the lowest epipelagic (0-100 m) polar cod larvae biomass in August 2013 (Geoffroy, 2016). Moreover, mesozooplankton (estimated length between 5 to12 mm) acoustic biomass derived from the 120 KHz frequency of the same ship mounted echosounder over the Mackenzie shelf in August of 2010, 2012, 2013 and 2014 revealed lower mesozooplankton biomass in 2013 (LeBlanc, in prep). These results indicate that the mismatch event of 2013 drastically affected the marine pelagic ecosystem of the Beaufort Sea.

However, *Calanus* copepods are well-adapted to extreme variations in environmental conditions and the negative effect of a low recruitment year may be dampened due to the multi-year life cycle of copepods, ranging from 1 to 3 years for *C. glacialis* and from 2 to 5 years for *C. hyperboreus* (Melle and Skjoldal, 1998; Falk-Petersen et al., 2009; Swalethorp et al., 2011; Wold et al., 2011; Daase et al., 2013; Hirche, 2013). Environmental conditions returned to a normal range during 2014-2015 deployment and following as reflected by water temperatures and ice conditions. Although there is no data available from September 2013 to September 2014, an increase in *nauplii* abundance in summer 2015 was followed by the largest *nauplii* abundance in 2016, reflecting the resiliency of the copepod community (Figure 7).

Mismatch events as the one observed in 2013 may become more frequent as the Beaufort Sea is susceptible to become ice-free more frequently in coming years (Babb et al., 2016). Sea ice is getting more scattered and dynamic due to the loss of multiyear ice and the lengthening of the ice-free period (Hutching and Rigor 2012; Galley et al., 2016). Such conditions allow the ice to drift and accumulate in areas that would normally be ice-free during spring and summer, suggesting that ice conditions similar to 2013 should increase in frequency.

The present assessment of long-term changes occurring at the Beaufort Sea shelf break is not possible with field sampling limited to ice-free periods in summer nor remote sensing. It is therefore crucial to maintain long-term observations in the Beaufort Sea and in the Arctic Ocean to better understand the wide range of effects induced by climate change.

Overall, the LTOO project provided crucial monitoring of variations in physical, biological and biogeochemical conditions in the Arctic Ocean. As long-term time-series increase in scientific value with time, it would be imperative to maintain the deployment of moorings in the rapidly-changing Arctic Ocean.

REFERENCES

Ardyna, M., Babin, M., Gosselin, M., Devred, E., Rainville, L., and Tremblay, J. É. (2014), Recent Arctic Ocean sea ice loss triggers novel fall phytoplankton blooms, Geophysical Research Letters, 41(17), 6207-6212.

Arrigo, K. R., van Dijken, G., and Pabi, S. (2008), Impact of a shrinking Arctic ice cover on marine primary production, Geophysical Research Letters, 35(19).

Ashjian, C. J., Campbell, R. G., Welch, H. E., Butler, M., and Van Keuren, D. (2003), Annual cycle in abundance, distribution, and size in relation to hydrography of important copepod species in the western Arctic Ocean, Deep Sea Research Part I: Oceanographic Research Papers, 50(10-11), 1235-1261.

Babb, D. G., Galley, R. J., Barber, D. G., and Rysgaard, S. (2016), Physical processes contributing to an ice-free Beaufort Sea during September 2012: ICE FREE BEAUFORT SEA SEPTEMBER 2012, Journal of Geophysical Research: Oceans, 121(1), 267-283.

Benoit, D., Simard, Y., Gagné, J., Geoffroy, M., and Fortier, L. (2010), From polar night to midnight sun: photoperiod, seal predation, and the diel vertical migrations of polar cod (*Boreogadus saida*) under landfast ice in the Arctic Ocean, Polar Biology, 33(11), 1505-1520.

Carmack, E. (2003), Wind-driven shelf/basin exchange on an Arctic shelf: The joint roles of ice cover extent and shelf-break bathymetry, Geophysical Research Letters, 30(14).

Conover, R. J., and Huntley, M. (1991), Copepods in ice-covered seas - distribution, adaptations to seasonally limited food, metabolism, growth patterns and life cycle strategies in polar seas, Journal of Marine Systems, 1-41.

Cota, G. F., Legendre, L., Gosselin, M., and Ingram, R. G. (1991), Ecology of bottom ice algae: I. Environmental controls and variability, Journal of Marine Systems, 2(3), 257-277.

Daase, M., Soreide, J., and Martynova, D. (2011), Effects of food quality on naupliar development in Calanus glacialis at subzero temperatures, MARINE ECOLOGY PROGRESS SERIES, 429, 111-124.

Daase, M., Falk-Petersen, S., Varpe, Ø., Darnis, G., Søreide, J. E., Wold, A., Leu, E., Berge, J., Philippe, B., and Fortier, L. (2013), Timing of reproductive events in the marine copepod *Calanus glacialis*: a pan-Arctic perspective, Canadian Journal of Fisheries & Aquatic Sciences, 70(6), 871-884.

Darnis, G., et al. (2012), Current state and trends in Canadian Arctic marine ecosystems: II. Heterotrophic food web, pelagic-benthic coupling, and biodiversity, Climatic Change, 115(1), 179-205.

Darnis, G., and Fortier, L. (2014), Temperature, food and the seasonal vertical migration of key arctic copepods in the thermally stratified Amundsen Gulf (Beaufort Sea, Arctic Ocean), Journal of Plankton Research, 36(4), 1092-1108.

Falk-Petersen, S., Pavlov, V., Timofeev, S., and Sargent, J. R. (2007), Climate variability and possible effects on arctic food chains: The role of Calanus, in Arctic Alpine Ecosystems and People in a Changing Environment, edited by J. B. Ørbæk, R. Kallenborn, I. Tombre, E. N. Hegseth, S. Falk-Petersen and A. H. Hoel, pp. 147-166, Springer Berlin Heidelberg, Berlin, Heidelberg.

Falk-Petersen, S., Mayzaud, P., Kattner, G., and Sargent, J. R. (2009), Lipids and life strategy of Arctic Calanus, Marine Biology Research, 5(1), 18-39.

Forbes, J. R., Macdonald, R. W., Carmack, E. C., Iseki, K., and Obrien, M. C. (1992), Zooplankton retained in sequential sediment traps along the Beaufort Sea Shelf break during winter, Canadian Journal of Fisheries and Aquatic Sciences, 49(4), 663-670.

Fortier, M., Fortier, L., Michel, C., and Legendre, L. (2002), Climatic and biological forcing of the vertical flux of biogenic particles under seasonal Arctic sea ice, MARINE ECOLOGY PROGRESS SERIES, 225, 1-16.

Galley, R. J., Babb, D., Ogi, M., Else, B. G. T., Geilfus, N. X., Crabeck, O., Barber, D. G., and Rysgaard, S. (2016), Replacement of multiyear sea ice and changes in the open water season duration in the Beaufort Sea since 2004, Journal of Geophysical Research: Oceans, 121(3), 1806-1823.

Geoffroy, M. (2016), Signature bioacoustique, distribution et abondance des poissons pélagiques et des mammifères marins en mer de Beaufort (Arctique canadien) une réponse à l'énigme de la morue arctique manquante, Thèse (Ph. D.) thesis, 1 ressource en ligne (xxiii, 149 pages) pp, Université Laval, Québec.

Gislason, A., and Astthorsson, O. S. (1992), Zooplankton collected by sediment trap mourred in deep water south of iceland.

Hirche, H.-J. (2013), Long-term experiments on lifespan, reproductive activity and timing of reproduction in the Arctic copepod *Calanus hyperboreus*, Marine Biology, 160(9), 2469-2481.

Hopcroft, R. R., Clarke, C., Nelson, R. J., and Raskoff, K. A. (2005), Zooplankton communities of the Arctic's Canada Basin: the contribution by smaller taxa, Polar Biology, 28(3), 198-206.

IPCC (2014), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Jackson, J. M., Carmack, E. C., McLaughlin, F. A., Allen, S. E., and Ingram, R. G. (2010), Identification, characterization, and change of the near-surface temperature maximum in the Canada Basin, 1993–2008, Journal of Geophysical Research, 115(C5).

Ji, R., Ashjian, C. J., Campbell, R. G., Chen, C., Gao, G., Davis, C. S., Cowles, G. W., and Beardsley, R. C. (2012), Life history and biogeography of *Calanus* copepods in the Arctic Ocean: An individual-based modeling study, Progress in Oceanography, 96(1), 40-56.

Ji, R., Jin, M., and Varpe, Ø. (2013), Sea ice phenology and timing of primary production pulses in the Arctic Ocean, Global Change Biology, 19(3), 734-741.

Jin, M., Deal, C., Lee, S. H., Elliott, S., Hunke, E., Maltrud, M., and Jeffery, N. (2012), Investigation of Arctic sea ice and ocean primary production for the period 1992–2007 using a 3-D global ice–ocean ecosystem model, Deep-Sea Research Part II, 81-84, 28-35.

Jung-Madsen, S., Nielsen, T. G., Grønkjær, P., Hansen, B. W., and Møller, E. F. (2013), Early development of *Calanus hyperboreus nauplii*: Response to a changing ocean, Limnology and Oceanography, 58(6), 2109-2121.

Kahru, M., Brotas, V., Manzano-Sarabia, M., and Mitchell, B. (2011), Are phytoplankton blooms occurring earlier in the Arctic?, GLOBAL CHANGE BIOLOGY, 17(4), 1733-1739.

Kiørboe, T. (1991), Pelagic fisheries and spatio-temporal variability in zooplankton productivity, Nihon Purankuton Gakkaiho (Special Issue), 229-249.

Kosobokova, K. N., and Hopcroft, R. R. (2010), Diversity and vertical distribution of mesozooplankton in the Arctic's Canada Basin, Deep Sea Research Part II: Topical Studies in Oceanography, 57(1-2), 96-110.

Kraft, A., Bauerfeind, E., and Nöthig, E.-M. (2010), Amphipod abundance in sediment trap samples at the long-term observatory HAUSGARTEN (Fram Strait, 79°N/4°E). Variability in species community patterns, Marine Biodiversity, 41(3), 353-364.

Kraft, A., Bauerfeind, E., Nöthig, E.-M., and Bathmann, U. V. (2012), Size structure and life cycle patterns of dominant pelagic amphipods collected as swimmers in sediment traps in the eastern Fram Strait, Journal of Marine Systems, 95, 1-15.

Lalande, C., Nöthig, E. M., Somavilla, R., Bauerfeind, E., Shevchenko, V., and Okolodkov, Y. (2014), Variability in under ice export fluxes of biogenic matter in the Arctic Ocean, Global Biogeochemical Cycles, 28(5), 571-583.

Lalande, C., Moriceau, B., Leynaert, A., and Morata, N. (2016), Spatial and temporal variability in export fluxes of biogenic matter in Kongsfjorden, Polar Biology, 39(10), 1725-1738.

Lavoie, D., Denman, K. L., and Macdonald, R. W. (2010), Effects of future climate change on primary productivity and export fluxes in the Beaufort Sea, Journal of Geophysical Research: Oceans, 115(C4).

Leu, E., Søreide, J. E., Hessen, D. O., Falk-Petersen, S., and Berge, J. (2011), Consequences of changing sea-ice cover for primary and secondary producers in the European Arctic shelf seas: Timing, quantity, and quality, Progress in Oceanography, 90(1–4), 18-32.

Liu, Y., and Key, J. R. (2014), Less winter cloud aids summer 2013 Arctic sea ice return from 2012 minimum, Environmental Research Letters, 9(4), 044002.

Makabe, R., Hattori, H., Sampei, M., Ota, Y., Fukuchi, M., Fortier, L., and Sasaki, H. (2010), Regional and seasonal variability of zooplankton collected using sediment traps in the southeastern Beaufort Sea, Canadian Arctic, Polar Biology, 33(2), 257-270.

Matsuno, K., Yamaguchi, A., Fujiwara, A., Onodera, J., Watanabe, E., Harada, N., and Kikuchi, T. (2015), Seasonal changes in the population structure of dominant planktonic copepods collected using a sediment trap moored in the western Arctic Ocean, Journal of Natural History, 49(45-48), 2711-2726.

McBride, M. M., et al. (2014), Krill, climate, and contrasting future scenarios for Arctic and Antarctic fisheries, ICES Journal of Marine Science, 71(7), 1934-1955.

Meier, W. N., et al. (2014), Arctic sea ice in transformation: A review of recent observed changes and impacts on biology and human activity, Reviews of Geophysics, 52(3), 185-217.

Melle, W., and Skjoldal, H. (1998), Reproduction and development of *Calanus finmarchicus, C-glacialis* and *C-hyperboreus* in the Barents Sea, MARINE ECOLOGY-PROGRESS SERIES, 169, 211-228.

Michaud, J., Fortier, L., Rowe, P., and Ramseier, R. (1996), Feeding success and survivorship of Arctic cod larvae, *Boreogadus saida*, in the Northeast Water polynya (Greenland Sea), Fisheries Oceanography, 5(2), 120-135.

Onodera, J., Watanabe, E., Harada, N., and Honda, M. C. (2015), Diatom flux reflects water-mass conditions on the southern Northwind Abyssal Plain, Arctic Ocean, Biogeosciences, 12(5), 1373-1385.

Ota, Y., Hattori, H., Makabe, R., Sampei, M., Tanimura, A., and Sasaki, H. (2008), Seasonal changes in nauplii and adults of *Calanus hyperboreus* (Copepoda) captured in sediment traps, Amundsen Gulf, Canadian Arctic, Polar Science, 2(3), 215-222.

Polyakov, I. V., et al. (2010), Arctic Ocean Warming Contributes to Reduced Polar Ice Cap, Journal of Physical Oceanography, 40(12), 2743-2756.

Poulin, M., Daugbjerg, N., Gradinger, R., Ilyash, L., Ratkova, T., and von Quillfeldt, C. (2011), The pan-Arctic biodiversity of marine pelagic and sea-ice unicellular eukaryotes: a first-attempt assessment, Marine Biodiversity, 41(1), 13-28.

Richter-Menge, J., Overland, J. E., and Mathis, J. T. (2016), Arctic Report Card 2016.

Ringuette, M., Fortier, L., Fortier, M., Runge, J. A., Bélanger, S., Larouche, P., Weslawski, J.-M., and Kwasniewski, S. (2002), Advanced recruitment and accelerated population development in Arctic calanoid copepods of the North Water, Deep sea Research Part II.

Seiler, D., and Brandt, A. (1997), Seasonal occurrence of planktic Crustacea in sediment trap samples at three depth horizons in the Greenland Sea, Polar Biology, 17(4), 337-349.

Søreide, J. E., Leu, E., Berge, J., Graeve, M., and Falk-Petersen, S. (2010), Timing of blooms, algal food quality and *Calanus glacialis* reproduction and growth in a changing Arctic, Global Change Biology, 16(11), 3154-3163.

Swalethorp, R., Kjellerup, S., Dunweber, M., Nielsen, T., Moller, E., Rysgaard, S., and Hansen, B. (2011), Grazing, egg production, and biochemical evidence of differences in the life strategies of *Calanus finmarchicus, C. glacialis* and *C. hyperboreus* in Disko Bay, western Greenland, MARINE ECOLOGY PROGRESS SERIES, 429, 125-144.

Tourangeau, S., and Runge, J. A. (1991), Reproduction of *Calanus glacialis* under ice in spring in southeastern Hudson Bay, Canada, Marine Biology, 108(2), 227-233.

Tremblay, J.-É., Simpson, K., Martin, J., Miller, L., Gratton, Y., Barber, D., and Price, N. M. (2008), Vertical stability and the annual dynamics of nutrients and chlorophyll fluorescence in the coastal, southeast Beaufort Sea, Journal of Geophysical Research, 113(C7).

Von Quillfeldt, C. H. (1997), Distribution of diatoms in the Northeast Water Polynya, Greenland, Journal of Marine Systems, 10(1), 211-240.

Von Quillfeldt, C. H., Ambrose, W. G., and Clough, L. M. (2003), High number of diatom species in first-year ice from the Chukchi Sea, Polar Biology, 26(12), 806-818.

Welch, H. E., and Bergmann, M. A. (1989), Seasonal Development of Ice Algae and its Prediction from Environmental Factors near Resolute, N.W.T., Canada, Canadian Journal of Fisheries and Aquatic Sciences, 46(10), 1793-1804.

Willis, K. J., Cottier, F., Kwasniewski, S., Wold, A., and Falk-Petersen, S. (2006), The influence of advection on zooplankton community composition in an Arctic fjord (Kongsfjorden, Svalbard), Journal of Marine Systems, 61(1-2), 39-54.

Willis, K. J., Cottier, F. R., and Kwaśniewski, S. (2008), Impact of warm water advection on the winter zooplankton community in an Arctic fjord, Polar Biology, 31(4), 475-481.

Wold, A., Darnis, G., Søreide, J. E., Leu, E., Philippe, B., Fortier, L., Poulin, M., Kattner, G., Graeve, M., and Falk-Petersen, S. (2011), Life strategy and diet of *Calanus glacialis* during the winter–spring transition in Amundsen Gulf, south-eastern Beaufort Sea, Polar Biology, 34(12), 1929-1946.

Zernova, V., Nothig, E., and Shevchenko, V. P. (2000), Vertical microalga flux in the northern Laptev Sea (from the data collected by the yearlong sediment trap), OCEANOLOGY, 40(6), 801-808.

PUBLICATIONS

Aulanier, F., Simard, Y., Bandet, M., Roy N., and Gervaise, C. 2017. Effects of shipping on marine acoustic habitats in Canadian Arctic estimated via probabilistic modelling and mapping. Marine Pollution Bulletin 125 (1): 115-131.

Dezutter, T. Lalande, C., Dufresne, C., Parenteau, M., Darnis, G., Fortier, L. To be submitted. Match-mismatch between phytoplankton and zooplankton in the Beaufort Sea. Global Change Biology.

Lalande, C., Grebmeier, J., Danielson S. To be submitted. Annual cycle of biogenic matter export on the Chukchi Sea continental shelf: 2015-2016. Geophysical Research Letters.

Pospelova, V., Lalande, C., Heikkilä, M., Fortier, L. To be submitted. Dinoflagellate cyst production in the presence/absence of sea ice cover in the Beaufort Sea (Arctic Ocean): one year sediment trap record. Marine Micropaleontology.

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

Project Team

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ABSTRACT

Climate change is altering Arctic marine ecosystem structure and function, and Arctic marine mammal populations (seals, whales, and polar bears) are vulnerable to direct loss of sea ice habitat, as well as associated indirect impacts such as changes in prey abundance. This project focuses on marine mammal ecology (e.g. diet, migration, and habitat use) and population demography (e.g. abundance and reproductive success) to understand how changes in sea ice patterns, food web structure, disease prevalence, and contaminant levels may impact Arctic marine mammal populations. A mix of scientific methods and traditional ecological knowledge are employed in various components of the study, and community-based monitoring programs to engage Northerners in research partnerships are incorporated. This integrated approach is providing a greater understanding of marine mammal populations and their Arctic environment, particularly in terms of defining critical habitat, early warning of change, and critical connections among ecosystem components. Results will help Northerners, who are culturally and economically reliant on these species, to develop adaptive conservation and management programs as marine mammal distributions and abundances respond to a changing Arctic ecosystem.

KEY MESSAGES

- Marine ecosystems are threatened by anthropogenic climate change and the Arctic is already experiencing pronounced warming and changes in sea ice dynamics (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 (for example, 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 provided 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 (Laidre et al. 2015).

RESEARCH OBJECTIVES

1. Quantifying marine mammal health, distribution, and abundance in response to environmental changes. We are examining how foraging strategies, body condition, and abundances are related to sea ice and other habitat characteristics.
2. Use a variety of analytical technologies such as satellite telemetry, stable isotope and fatty acid biomarkers, contaminant and mercury profiling and genetic techniques to better understand the ecological links of marine mammals and their environment. Specifically, we are refining existing techniques to improve our analyses and we are looking at developing new non-invasive techniques to address our research questions.
3. Engage with northern communities and extend our research network to involve community members and hunter and trapper organizations as much a possible in the creation, execution and reporting of our scientific research, e.g., community based monitoring and harvest sampling and data collection. We also incorporate Inuit Qaujimatuqangit as a component to science-based methods to understand marine mammal ecology in the north.
4. Develop statistical and mathematical models that integrate data on Arctic marine mammals with climate, sea ice and oceanographic data to identify species sensitivities and quantify possible regime shifts that may be occurring related to a warming Arctic.

KNOWLEDGE MOBILIZATION

Our research group has mobilized scientific knowledge through various public outreach activities, including classroom visits, public seminars and northern community meetings. Graduate students in Winnipeg, Manitoba participated in the annual Arctic Science Day at Fort Whyte Alive in March 2017 where they interacted with over 200 students in grade 5 – 12. Hands on activities included identifying marine mammal teeth and bones, exploring various research techniques like photograph identification and aerial survey counts (Figure 1). Students also participated in ringed seal stomach dissections simulated with Jell-O and beads to further understand changes in the Arctic food web (Figure 1). Educational opportunities such as this are important for students to be exposed to various aspects of Arctic research. Six graduate students plan on delivering programs during the 2018 Arctic Science Day being held in March 2018.

Several of our graduate students prepared media releases in conjunction with publications of their thesis research or research proposal, fieldwork updates. For instance, doctoral student Sarah Fortune released a publication about bowhead whale moulting, and received attention on social media outlets, such as Twitter as well as local news broadcasts and prints. Master's student, Justine Hudson communicated her non-invasive beluga research with CBC Manitoba explaining how beluga "snot" can help track beluga stress in Manitoba. Polar bear research is also communicated to a general audience on Twitter (@AEDerocher).

Doctoral student, Cassandra Debets, delivered a full day ringed seal health and contaminants workshop for students in Sachs Harbour, Northwest Territories in collaboration with scientists at Environment and Climate Canada in January 2017 (Figure 2). There is a planned workshop scheduled in Arviat in the fall

Figure 1. Students in Winnipeg, Manitoba participating in marine mammal research activities at Arctic Science Day 2017 at Fort Whyte Alive. (A) Students are examining narwhal, beluga aerial survey photographs, (B) students are comparing coloured photographs with infrared photographs from ringed seal aerial surveys, and (C) students are using taxonomic keys to identify coloured beads that represent ringed seal prey items in a simulated stomach contents analysis.

Figure 2. Students in Sachs Harbour, Northwest Territories participating in a full day ringed seal health workshop delieverd by Environment and Climate Change Canada and Doctoral student Cassandra Debets. (A) Students learning how marine mammals can be monitored, (B) students learning about the Arctic marine food web, (C) students using taxonomic keys to identify coloured beads that represent ringed seal prey items in a simulated stomach contents analysis, and (D) students observing living zooplankton under microscopes.

of 2018, which members of our research team are involved in planning, and Cassandra will help deliver the program to students. Maha Ghazal presented her research to local Pangnirtung grade 7-9 students. Northern classroom visits are an excellent way for our research team to communicate our results and foster working relationships with northern communities.

AARLUK newsletter is sent to northern communities to disseminate Arctic killer whale field results, ongoing analysis and expect results. This communication tool is a source of community involvement and communication with southern researchers. The research group also maintains social media (Twitter and Facebook) pages to share results and updates as well as other Arctic cetacean science. Northern community members are encouraged to share their knowledge, such as sightings on the group page.

A community visit to Pond Inlet in March 2017 took place to communicate results from the 2016 seal survey and to propose 2017 research (Seal collections, seal tagging, aerial survey) to Hunter and Trappers Organization (HTO) board. Following research activities a summary report was provided to Mittimatilik HTO in Pond Inlet. Following the 2016 tagging of bowhead whales in Cumberland Sound, regular emails to update on bowhead movements were provided to community HTOs, funding partners, and colleagues. These updates continued until May 2017 when all satellite transmitters stopped providing data. Meetings with Pangnirtung HTO board took place in August 2017 to discuss bowhead whale research in Cumberland Sound, and to disseminate the findings of our bowhead whale moulting study. We also coordinated filming with the Nature of Things to incorporate Inuit perspectives in their documentary on the biological application of drones, which is highlighting our bowhead drone research. A completed summary report on field activities was provided to Pangnirtung HTO following completion of 2017 fieldwork.

Narwhal habitat selection results are being translated and sent to the HTO's of Arctic Bay and Pond Inlet, which were the communities involved in equipping the narwhals with satellite telemetry tags. Distribution of satellite-tracked polar bears continues to be disseminated weekly to appropriate government (e.g. Nunavut biologists, Manitoba biologists and conservation officers) and Indigenous groups and local community members.

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 monoceros*; bowhead whales, *Balaena mysticetus*; and polar bears, *Ursus maritimus* to answer the following questions:

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

We collected 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 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 analyzing steroid hormone levels as a proxy for stress and contaminants analysis to track pollution and uptake into marine mammal tissues. Genetic profiling is allowing us to estimate population size and structure, and trend while genomics will allow us to assess the ecological linkages to population demography. 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 combined scientific and traditional ecological knowledge and allowed 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 hunters through the hunter and trapper organizations.

ACTIVITES

Current research is to coordinate monitoring and conducting analyses of marine mammals in the Canadian Arctic. S. Ferguson is a member of the Marine Mammal Expert Network (within Conservation of Arctic Flora and Fauna (CAFF)) and has focused this ArcticNet project on efforts to develop and coalesce databases of relevant demographic, distribution, and condition information for all populations of marine mammals, with numerous collaborators. Recently, past abundance and harvest estimates were summarized to establish historic baselines and trends as a reference for future monitoring. Existing data sets have been identified, aggregated and analyzed to establish indicator baselines on abundance of marine mammals. Future efforts will focus on summarizing Canadian Arctic marine mammal body condition, health databases, and telemetry movement/distribution.

We had a few new students join our project this year to explore new questions with existing archived data that had not yet been analyzed. Particularly, members of our group worked at collaborating with several Arctic ecologists to compile existing telemetry data for several marine predators to determine areas of importance for multispecies during summer-autumn and winter-spring with implications on conservation and management policy across the North American Arctic. Spatiotemporal hotspots across a significant portion of the Arctic, from eastern Russia to West Greenland, using telemetry data from 1282 individuals from 21 species across pinniped, cetacean, seabird, polar bear and fish species groups. In addition, existing students continued to refine their analyses and explore previously acquired data, and also collect data from summer fieldwork in 2017. A majority of our graduate students were afforded the opportunity to attend the ArcticChange meeting in Quebec City to present their ArcticNet graduate research.

Bears

Polar bear research in 2017-2018 focused on the analysis of existing archived samples from polar bears in several populations across Canada. A majority of the research was aimed at monitoring population changes in response to climate change, which will be used by several M.Sc. and Ph.D. students. Many activities were conducted with Environment and Climate Change Canada to analysis previously collected field samples (i.e., hair, blood, teeth) from

Western Hudson Bay and Beaufort Sea subpopulations. New techniques to analyze common biological samples were conducted to develop new long-term indices. Continued refinement of techniques and development of new less invasive techniques were a priority to monitor polar bear populations.

The following activities were completed in 2017-2018:

- 3500 polar bear premolars were analyzed for environmental trend signatures. Ringed seal teeth were also analyzed to determine a long-term index of reproduction that has been used to assess the Beaufort Sea subpopulation.
- Carbon and Nitrogen stable isotope signatures were analyzed from 1500 samples of polar bears from the Beaufort Sea and Western Hudson Bay.
- Polar bear movement was analyzed using satellite telemetry data, and is now largely focused on long-term (ca. 14 years) of movement data relative to sea ice dynamics in the Hudson Bay.
- Polar bear diet estimates from three subpopulations were analyzed with collaborators using a novel technique (H-print) to determine if Carbon, an energy source, was derived from ice associated or pelagic species.
- Microelements in polar bear hair were analyzed using laser ablation revealed a new means of assessing temporal variation in polar bears and may yield insights into feeding dynamics. Additionally, mercury was also measured in hair for approximately 500 samples and is being integrated with isotopic data.
- Field sampling was conducted in Western Hudson Bay in the spring and autumn in conjunction with Environment and Climate Change Canada and the Manitoba Government to monitor the movements and demography of Western Hudson Bay polar bears.

Whales

Research on Arctic whales (narwhal, beluga and bowhead) was focused largely on understanding movement in relation to seasonal sea ice regimes. Research on ice-associated whales (sperm and northern bottlenose whales) was focused on refined habitat selection analysis. Another main focus of cetacean research used archived tissue samples from community harvests (i.e. Narwhal tusks) for diet analysis. New research projects focused on quantifying cortisol levels in the Western Hudson Bay beluga population using non-invasive techniques. Beluga whale research also used passive acoustic monitors as another non-invasive measure of determining habitat selection. We are improving abundance estimates of Killer whales using photo-identification in the eastern Canadian Arctic.

Activities completed in 2017-2018:

- Narwhal home-range analysis was completed using Archival satellite tag data and provided the foundation for a M.Sc. student's thesis. The thesis was completed in July 2017 and described narwhal movement, summer and winter home-range overlap between two narwhal stocks (Admiralty Inlet and Eclipse Sound), finally narwhal winter habitat selection was described using sea ice structure and bathymetry information.
- 21 Narwhal tusks from 2015 and 33 tusks collected in 1982 were photographed and drilled using a micromill drill along dentine growth layer groups (Figure 3) to assay stable isotope analysis and provide information on individual narwhal diet specialization.
- Beluga predation was modelled to examine seasonal and decadal (1982 – 2012) shifts in asymmetric intraguild predation among other predators in Cumberland Sound (e.g. ringed seals and Greenland habitat).
- Determine prey contributions to the diet of beluga, ringed seals, Greenland halibut and Arctic

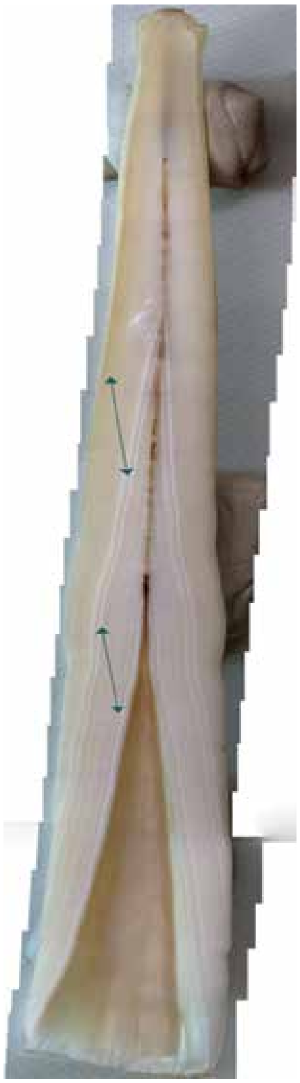

Figure 3. A cross section of a Narwhal tusk that will be used to analyze dentine growth layer groups for individual diet estimations. Photo Credit: C. Matthews, Fisheries and Oceans Canada.

char, quantify predator niche sizes and apply six community-wide metrics to characterize the trophic structure of this near apex predator assemblage in Cumberland Sound, Nunavut, Canada.

- Beluga summer habitat selection was analyzed by passive acoustic monitoring and automated detectors to determine habitat use in Clearwater Fiord by Cumberland Sound Beluga and the number of contact calls made between populations. This analysis also investigated the efficiency of an automated detector to reduce manual analysis of a large dataset.
- 233 beluga respiratory condensate samples were non-invasively collected from the Churchill estuary throughout July with help from Sea North Tours and Fisheries and Oceans Canada. These samples will be processed for cortisol concentrations to establish baseline stress levels in the population.
- Killer whales were photographed at Kakiak Point in August through collaborations with the Arctic Bay HTO and Fisheries and Oceans Canada personnel.
- Sperm and bottlenose whale sightings in Baffin Bay and Davis Strait (BB-DS) were mapped and then associated with the basin's physical parameters (sea surface temperature, sea surface salinity, depth and slope) to determine important habitat for these species. The analyses completed this year help refine the results and was submitted for publication.
- Bowhead whale diet was analyzed for zooplankton species composition and abundance, and feeding behaviour was analyzed from aerial observations using drones, and movement recordings using archival tags.
- Bowhead whale fieldwork took place in Cumberland Sound and plans were made in consultation with the Pangnirtung Hunters and Trappers Association. A local field guide and assistant were hired to drive boats, assist with biopsy collection, logistics, and to provide advice based on local knowledge. The field work was done in August, during the time in which bowhead whales are abundant in Cumberland Sound, particularly in Kingnait Fiord. Field teams were based out of Pangnirtung and performed day trips, primarily to the area in and around Kingnait Fiord.

Seals

Seal research during 2017-2018 primarily used tissues collected from northern community subsistence harvests. Many of the samples were used to investigate ringed, harp and bearded seal diets in Hudson Bay and Cumberland Sound. Diet studies used a variety of methods including stomach contents, stable isotope and fatty acid analyses. Other studies were dedicated to determining seal abundance from aerial survey data in Western Hudson Bay and around Pond Inlet, and determining effective population size from genetic analysis of Arviat seal harvest samples.

Activities completed in 2017-2018:

- Community-based sample collections of ringed seal tissues continued in 2017, with sample collections from the communities of Arviat, Sanikiluaq, Kugaaruk, Resolute, Pond Inlet, Pangnirtung, and Naujaat. To date, tissues samples from 2017 were collected from approximately 250 seals.
- Collaborations with the Government of Nunavut Fisheries and Sealing Division and the Wildlife Officers stationed in communities, samples from ringed seal pelts were obtained from Pangnirtung, Kugaaruk, and Cape Dorset.
- Ringed seal diet and foraging ecology in the Baffin region were analyzed by completing Interviews with hunters from Arctic Bay in the winter of 2017. Interview notes and audio was transcribed and spatial information digitized. Diet was assessed by quantitative measures using stomach contents for Arctic Bay, Pangnirtung, and Pond Inlet communities.
- The short-term and long-term diets of ringed and harp seals in Cumberland Sound were quantified and compared using stomach content analysis and stable isotope analyses.
- Vibrissae samples from ringed seals previously satellite tagged around the Belcher Islands, Nunavut were analyzed for stable isotope signatures and were compared to benthic dive behaviours.
- Ringed and bearded seal blubber samples collected from Hudson Bay communities (Arviat, Naujaat and Sanikiluaq) were extracted for ongoing fatty acid analysis to quantify diet.
- Spring aerial surveys of hauled-out ringed seals were based out of Churchill, MB and Pond Inlet, NU. 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. Surveys were flown at a target speed of 110 knots (204 km/h) ground speed (to make it easier for the pilots to maintain a level pitch), and a target altitude of 1000 ft. Infrared videos were recorded within a 250 m strip beneath the aircraft and potential seals were verified using corresponding images from a digital single-lens reflex camera.
- Analysis of strip transects analysis of infrared data were compared to results from strip transect analysis of visual observer data and to results from line transect analysis of a combined data set of infrared and visual observer data.
- Ringed seal effective population size was genetically estimated using harvest samples and compared to population abundance derived from aerial surveys; additionally, trends in effective population size were compared to trends in environmental variables (date of spring breakup, date of fall freeze up, snow depth, and spring rainfall).
- Two ringed seals were fitted with satellite telemetry transmitters in Tremblay Sound in August 2017 to study movement ecology of ringed seals as part of a larger ecosystem project being conducted in the area.

RESULTS

Bears

The development of biomarkers to help assess whether polar bear health is impacted by long-term environmental change has been the focus of our research program. We have focussed on analysis of stable isotopes, fatty acids, mercury, and cortisol levels. These data are now being integrated with satellite telemetry data to obtain a more holistic view of change in polar bears. Analyses have reveal spatial variation in many of the metrics suggesting that part of the variation in demographic responses between bears is associated with where they live within a population. We have completed laboratory analysis of polar bear hair and claw samples from western Hudson Bay and the Beaufort Sea for stable isotopes of carbon and nitrogen and analyses are ongoing. From ringed seal canines collected from seals killed by polar bears, we developed an index of annual growth that was correlated with ovulation rate obtained independently from harvest monitoring data. This index allowed for the creation of a continuous index of ringed seal condition spanning 1965-2007.

Whales

Narwhal movement studies revealed more varied movement patterns in both the summer and winter seasons compared to previous tagging studies. There was overlap in summer and winter home-ranges between the two narwhal stocks (Admiralty Inlet and Eclipse Sound). Narwhals selected areas where bathymetric depths were 1500-2000 m and avoiding areas where bathymetric depths were <1000 m. They avoided areas with landfast ice. They selected for areas where ice concentration was >95% and <35%.

Beluga presence and absence was correctly identified by an automated detector with >85% accuracy, and detected 42% of manually annotated vocalizations. Manual annotation detected a greater number of calls; however, this bias was consistent when compared to automated detections (R^2=0.79, p<0.001) (Figure 4). Between years, similar patterns in vocalization activity were observed. Overall vocalization activity was highest at the northernmost sites, farthest from the fiord's entrance, and was observed to exhibit a diurnal pattern. Sites that were further south in the fiord displayed lower vocalization levels, while the southernmost site, located at the entrance of the fiord, had negligible vocalization levels (Figure 4).

Using stable isotope signatures from belugas, ringed seal, Greenland halibut and Arctic char in the Cumberland Sound area provided the first empirical evidence of long-term (1990 – 2012) alteration to the trophic structure of an Arctic ecosystem. Change was driven by dietary and isotopic niche shifts among near-apex predators associated with changes in the composition of forage fish species availability coincident with a rapidly warming climate (Figure 5). The total isotopic niche space decreased, indicating that predators were converging on similar prey species, capelin, in the 2000s compared to the 1990s, when there was a larger isotopic niche space occupied by the four marine predators.

During summer 2017, fieldwork out of Arctic Bay in Admiralty Inlet encountered killer whales but the field team was unable to approach for ID photos, biopsy samples, or deploy satellite tags. However, numerous sightings in the Eclipse Sound, Pond Inlet area resulted in ID-quality photos necessary to develop a catalogue and initiate abundance estimation methods. From northern communities, we collected 15 sightings of killer whales including the Pond Inlet area, Admiralty Inlet, Lancaster Sound, Hudson Strait, Qikiqtarjuaq, and Cumberland Sound. Researchers continued analysis of samples and data collected in previous years. Killer whale skin and blubber biopsies collected since 2017 have been analyzed for stable isotopes, fatty acids, contaminants, and genetics. Currently manuscripts about killer whale diet and foraging ecology are in preparation. We have also analyzed tracking data of simultaneously tagged killer whales,

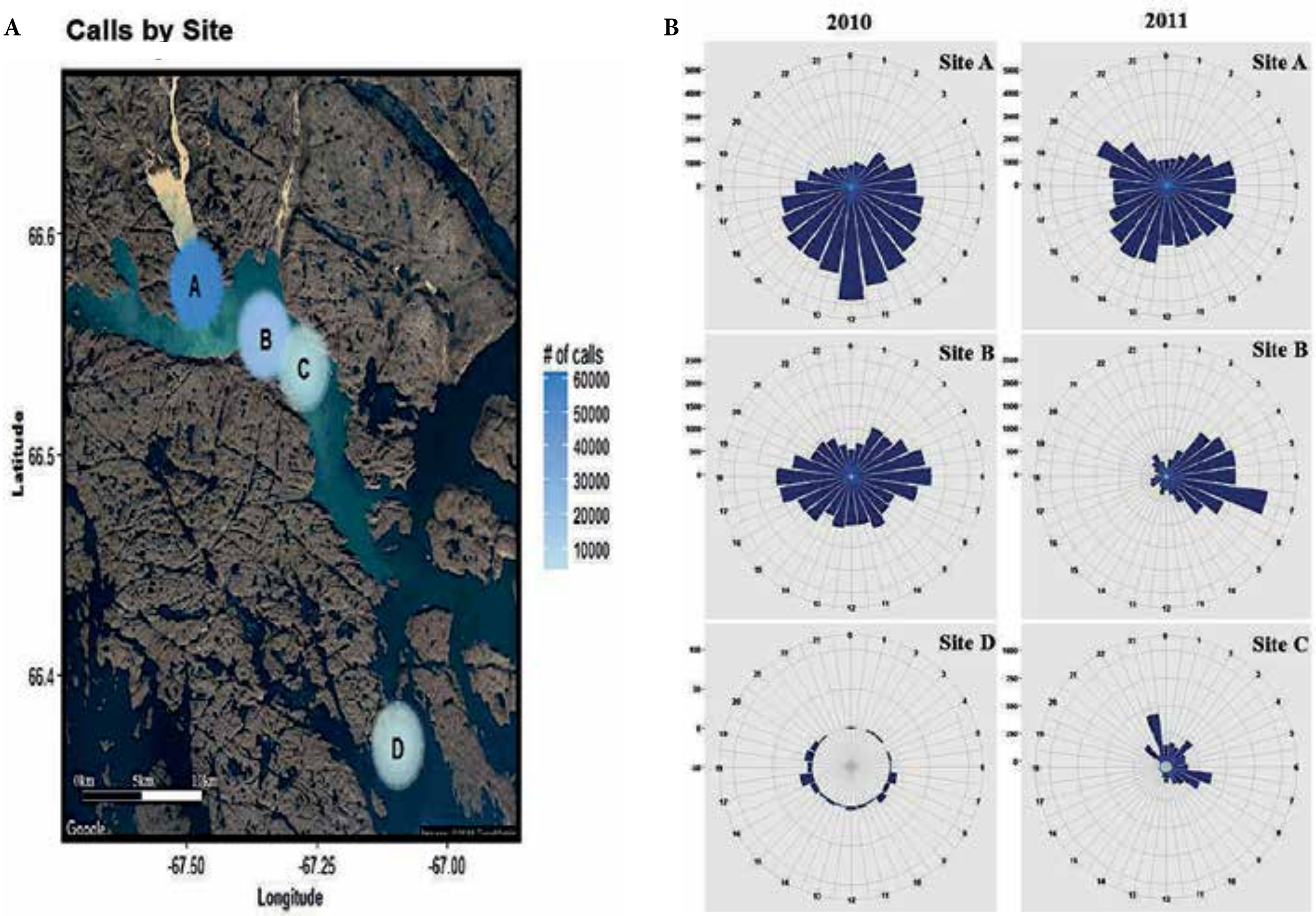

Figure 4. Results of passive acoustic monitors for beluga presence in Cumberland Sound area. (A) Averaged number of beluga calls per deployment site. Sites A and B are displayed as an average number of calls across both deployment years as these sites were replicated. Sites C (2011) and D (2010) display single year results only. (B) Polar plots displaying number of calls per hour at each recording site, across deployment years.

narwhals, and bowhead whales to describe killer whale impacts on prey species behavior.

Sperm and northern bottlenose whale habitat selection had previously been analyzed and was continued to be refined for publication. Little is known about how sperm whales (and northern bottlenose whales) use their Arctic habitat. In order to gain an understanding of their habitat preferences, cetacean presence data for Baffin Bay and Davis Strait (BB-DS) were mapped and then associated with the basin's physical parameters (sea surface temperature, sea surface salinity, depth and slope). A GIS was used to visualize the spatial patterns and cetacean density from the sightings within BB-DS. Generalized additive models were also created to understand the relationship between the whale presence and environmental variables. Summarizing the presence of sperm and northern bottlenose whales within BB-DS waters has not been done before and is helping us to begin to understand what habitat types they may prefer (Figure 6).

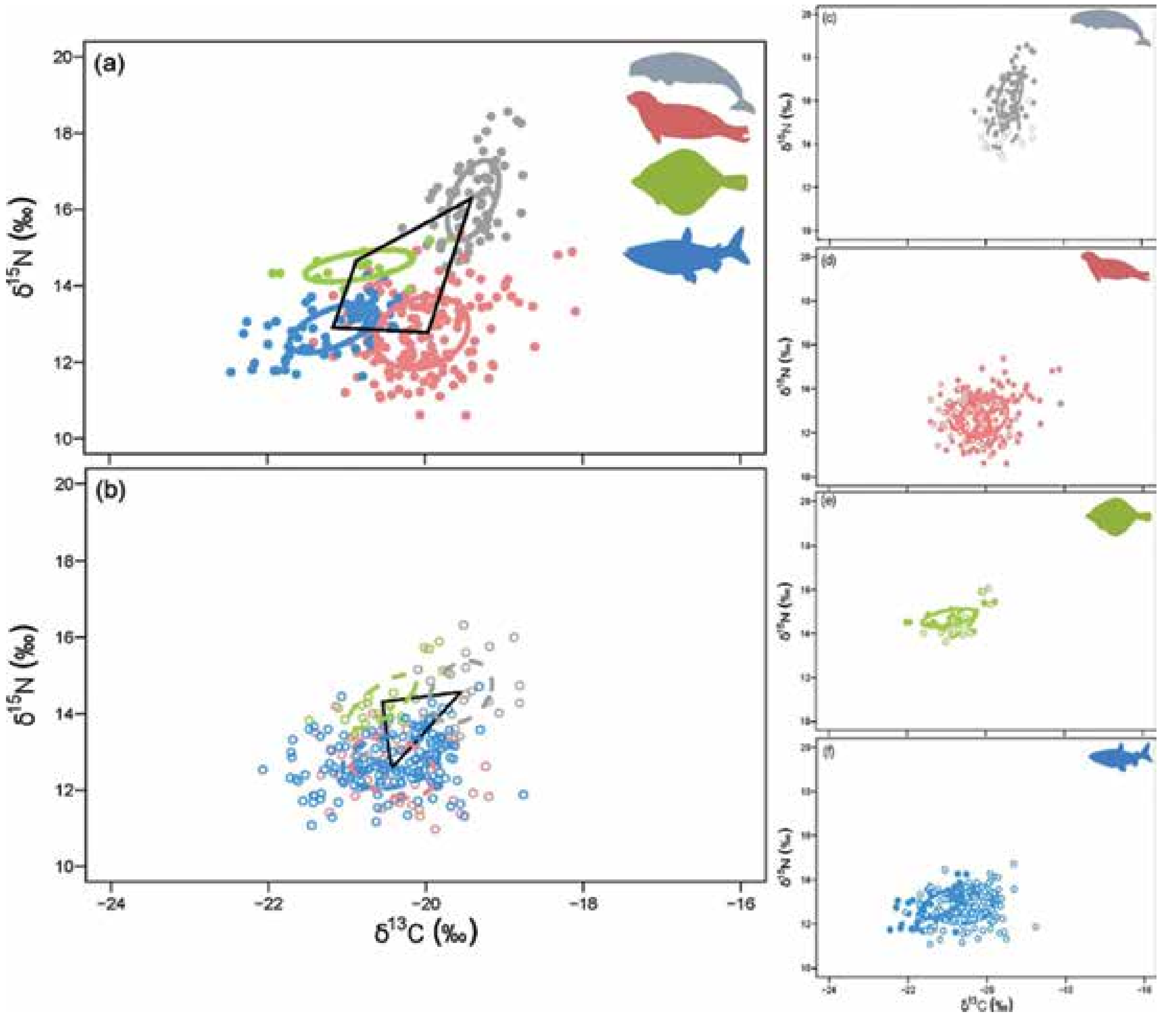

Figure 5. Stable isotope bi-plot representing the 40% isotopic niche sizes of beluga, ringed seals, Greenland halibut and Arctic char during 1990-2002 (solid lines; (a)) and 2005-2012 (dashed lines; (b)) with solid black lines characterizing the community metric of total area. Panels (c), (d), (e) and (f) represent isotopic niche shifts for each predator species between both time periods.

Bowhead whale fieldwork in Cumberland Sound took place over a 10-day period from 15-24 August 2017, a total of 7 days of at-sea work were conducted in Cumberland Sound. In total, 108 bowhead tissue biopsy samples, 1014 bowhead photographs, and 222 beluga photographs were collected. The majority of biopsy samples were collected in the western end of Kingnait Fiord. Bowheads that may have been present further into Kingnait Fiord were generally inaccessible as high winds and large waves prevented access to most of Kingnait Fiord on most days.

One hundred and eight biopsy samples and over 1000 photographs were collected. Analysis of UAS photographs is ongoing, but preliminary analyses have identified 81 unique individual bowheads in the photographs collected in 2017. Ongoing analysis will obtain measures of length and body condition wherever possible, and individual whales will be scored on re-identifiability and photo quality then compared to 2016 photos to determine any re-sightings between years.

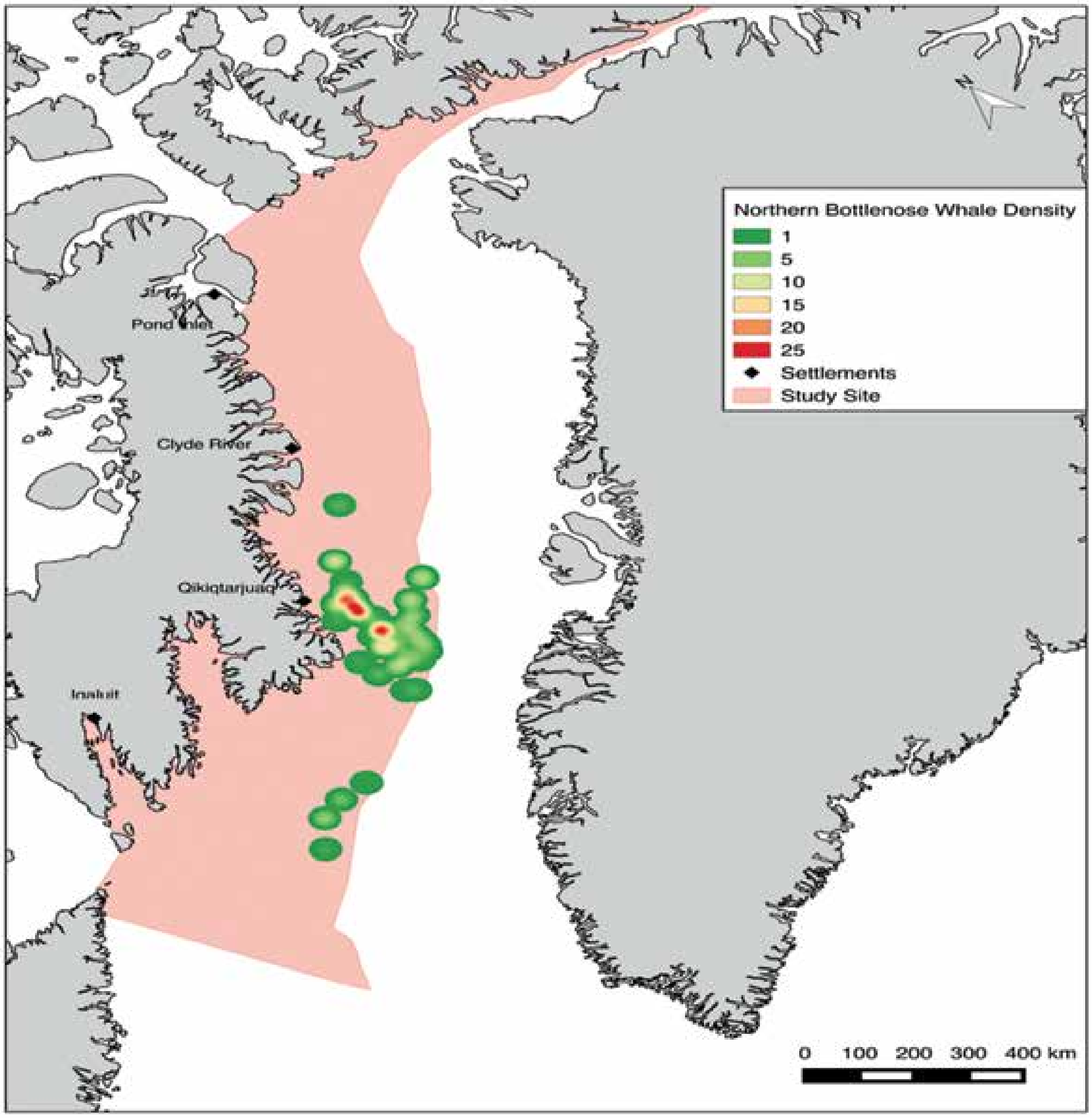

Figure 6. Heatmap of northern bottlenose density on the west region of the study site. Output from QGIS calculates sightings per area (30 km radius).

Based on movement and diet, bowhead whales are targeting two discrete prey layers in Cumberland Sound, Nunavut. The whales were conducting shallow feeding dives (20-50 m) to exploit smaller bodied, lower-energy prey and conducting deeper dives (150-200 m) to feed on prey layers dominated by larger organisms that are comparatively higher in energy content. Vertical prey sampling revealed two prey layers comprised of almost exclusively Calanoid copepods at depths that correspond to bowhead whale dive depths. Zooplankton biomass was dominated by lipid rich, Arctic copepods (e.g., *Calanus hyperboreus* and *C. glacialis*).

Seals

To date, tissue samples from 2017 were collected from over 200 seals as part of the community-based sample collection program (Arviat, Sanikiluaq, Pond Inlet, Resolute, Pangnirtung, Naujaat, Kugaaruk, and Holman). Several graduate students use these tissues that are provided for their thesis work and analysis is ongoing.

Baffin ringed seal stomach content analysis of all prey consumed indicates that in the southern community of Pangnirtung there has been a shift from predominantly fish in the diet (80% fish to 20% invertebrates) in the 1990s (n = 44) to a greater portion of invertebrates (52% fish to 48% invertebrates) in the 2000s (n = 53). The same pattern is not as clear in northern Baffin Island, the shift from the 1990s (n = 47) to the 2000s (n = 15) has actually lead to an increase in fish consumed (from 88% to 96%). Qualitative results from interviews with community members is currently being processed and will be used in conjunction with stomach content data to better understand ringed seal foraging around Baffin Island.

Stomach content analysis of ringed and harp seals in Cumberland Sound reveal similar main prey groups are consumed by both species (Figure 7); however, they differ somewhat in the proportions that each prey group represents in the diet. While both species consume and greater proportion by number of invertebrates, harp seals eat a greater proportion of fish than do ringed seals. When converted to biomass and energy (to account for the bias that exists toward small, numerous prey such as invertebrates), fish are more a dominant prey type in the diet. Still, harp seals

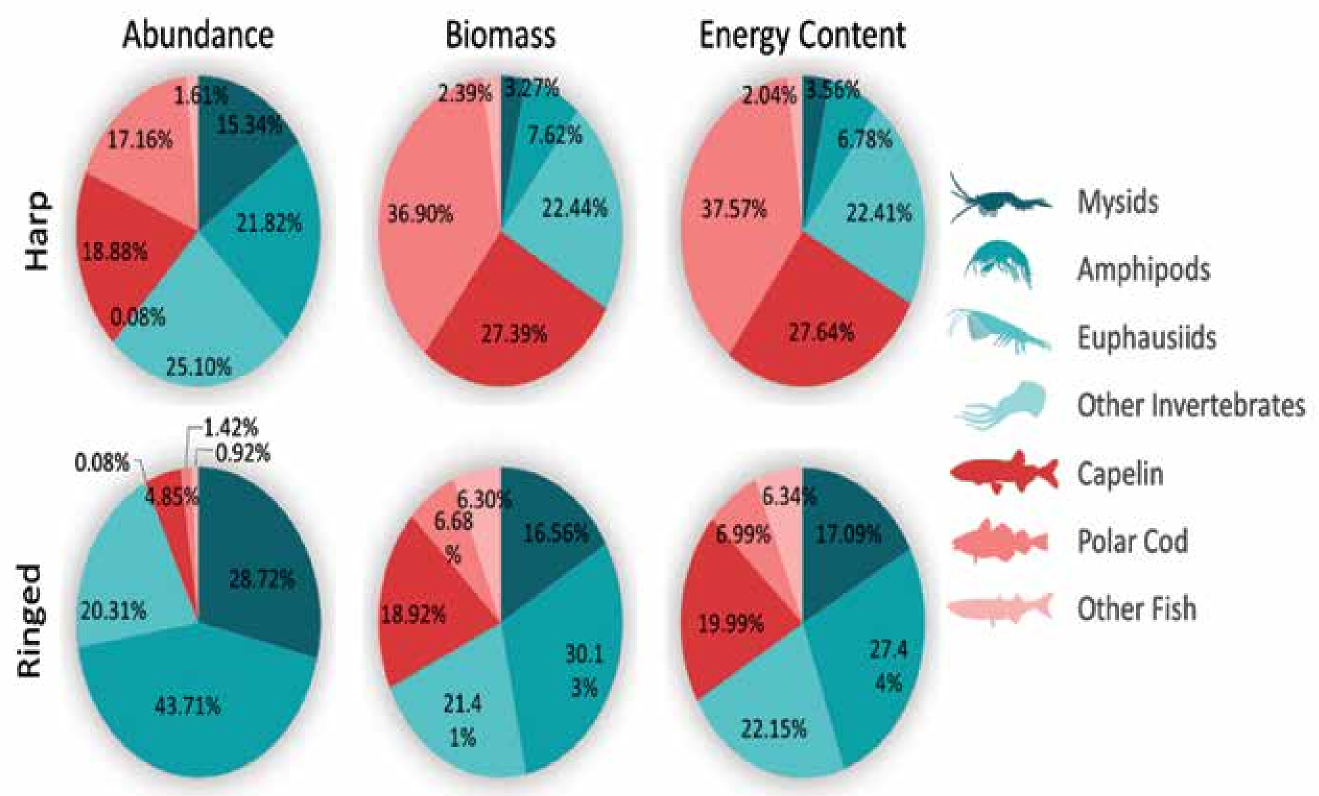

Figure 7. Mean percent composition of prey items found in the stomachs of ringed and harp seals captured in Cumberland Sound from 2008-2010 and 2015-2016 during the open water period. Seals of all ages are grouped. Percent of total average diet is shown based on mean abundance, mean dry biomass, and mean energy content. (n= 18 harp seals and 65 ringed seals).

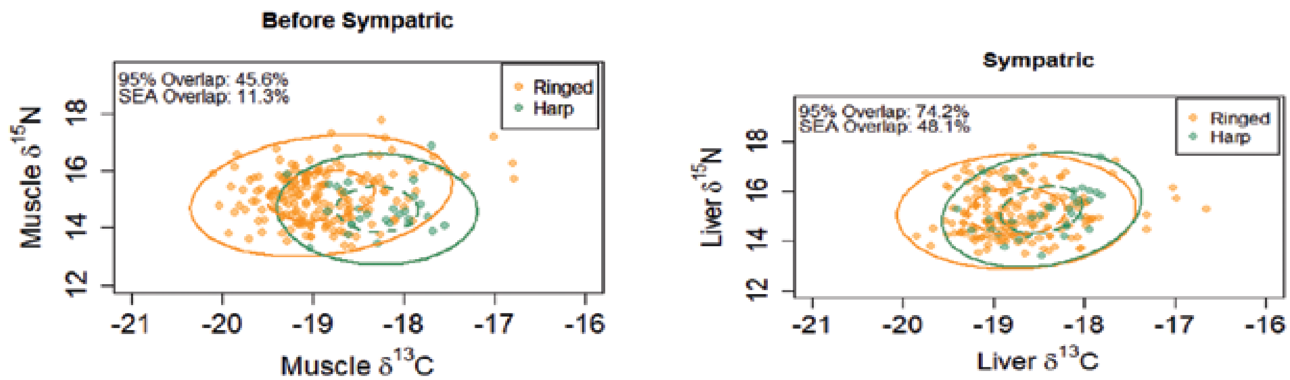

Figure 8. Carbon and nitrogen stable isotopic niches of ringed and harp seal muscle (left) and liver (right) tissues. Both standard ellipse and 95% prediction ellipses are shown. Ellipse overlap is denoted. Figure includes seals of all ages sampled during the open-water period in Cumberland Sound from 2008-2010 and 2015-2016.

consume a greater proportion of fish than do ringed seals. Schoener's Index for dietary overlap indicated that, when all ages are grouped, overlap is ecologically meaningful ($\alpha \geq 0.60$; Schoener 1970, Wallace 1981) using energy content and biomass, but not when using abundance.

Stable isotope analysis revealed that ringed and harp seal isotopic niche overlap increases during the time when they co-occur in Cumberland Sound. Muscle tissue, which represents long-term diet before harp seals migrate to Cumberland Sound, indicated an isotopic niche overlap of 45.6% (Figure 8). Liver tissue, representing the long-term diet during the time when ringed and harp seals are sympatric, indicated an isotopic niche overlap of 74.2% (Figure 8).

Vibrissae samples from live-captured ringed seals revealed that many seals have individual foraging strategies and many seals do not display dietary consistency over an approximate six-month period. Stable isotope mixing model, MixSIAR, revealed that only one adult male seal had dietary consistency, where cod represented over 83% of prey consumed (Figure 9). The mixing model revealed that sandlance and capelin represented large portions of the diet compared to other areas where Arctic cod are the dominant prey type. Adult ringed seals showed more interspecific variability than juveniles (Figure 9).

Ongoing analysis using fatty acids and stable isotopes will further reveal patterns in Hudson Bay ringed seal foraging. Previously satellite tagged ringed seals around the Belcher Islands was analyzed for stable isotope signatures and were compared to benthic dive behaviours. Dive behaviour data obtained from satellite tags revealed that seals that spent a greater portion of time near the ocean bottom also had higher $\delta^{13}C$ values, reflecting that those seals diet signatures were benthic. Using both approaches to understand foraging ecology of ringed seals provided more holistic results.

Aerial surveys of ringed seals in Western Hudson Bay and in the area of Pond Inlet were completed in late May and early June 2017. Due to poor weather conditions, only 4 out of the planned 10 transects in western Hudson Bay could be completed while 2 out of 3 strata out of Pond Inlet were completed. Density estimates ranged from a low of 0.24 ringed seals per km^2 on one survey of Navy Board Inlet, to a high of 2.05 seals per km^2 in the nearshore area of western Hudson Bay. Results obtained from infrared imagery were compared to results obtained from human observers in the plane. The infrared survey methods produced higher density estimates, approximately 2 to 3 times higher than traditional methods using human observers (Figure 10).

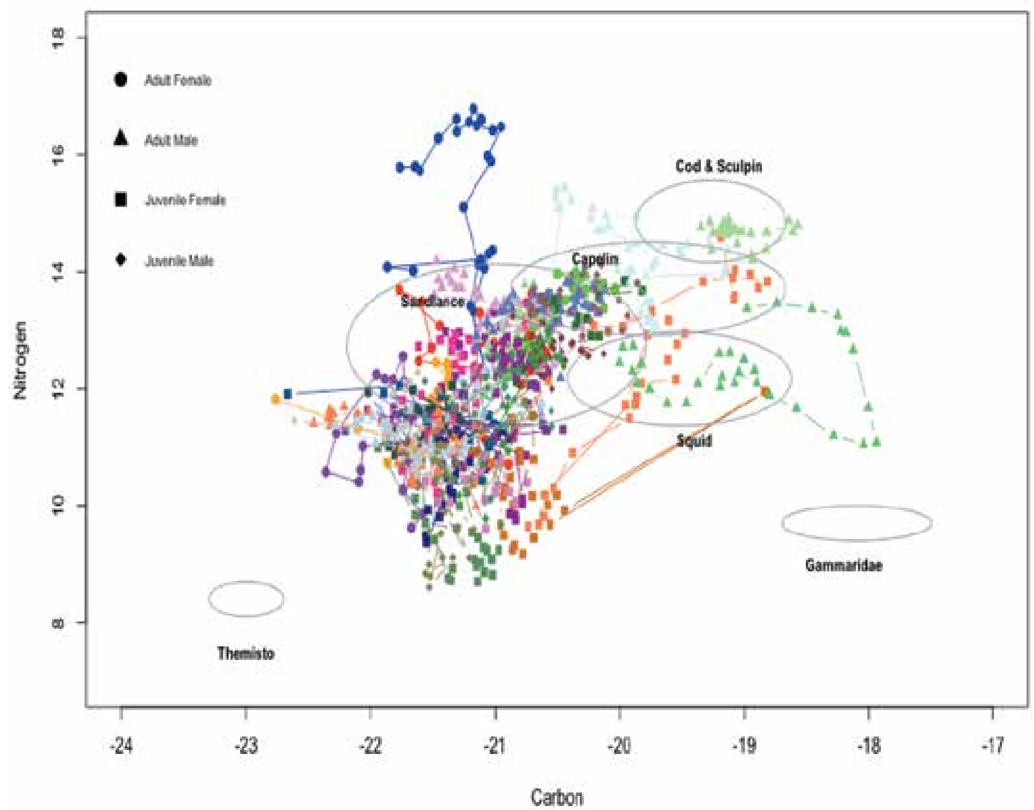

Figure 9. Isotopic biplot for vibrissae segements collected from 40 ringed seal captured between 2006 -2012 around the Belcher Islands in Hudson Bay. Each colour represents an individual seal. Adult males (triangle) occupy areas with higher Carbon and Nitrogen values and there is inter-individual variation between seals in the same age and sex classes (light green triangle vs. light blue triangle).

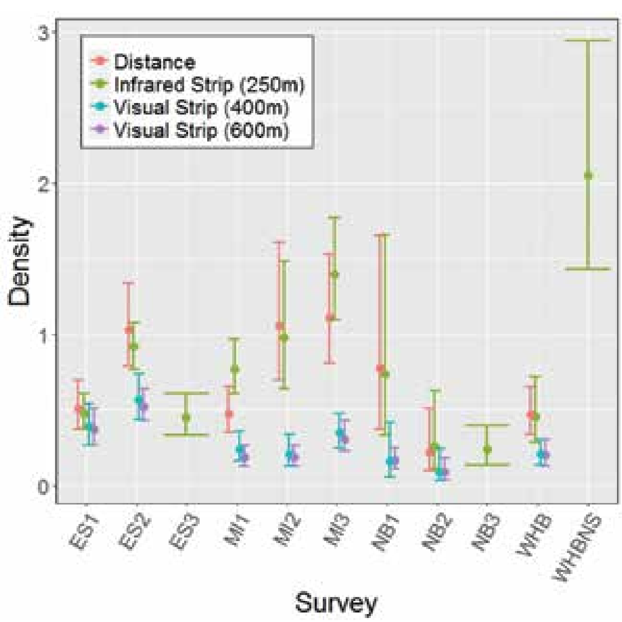

Figure 10. Density estimates from aerial surveys of ringed seals in 2016 and 2017. The infrared strip transect and the line transect analyses produced similar density estimates, which were both significantly higher than the strip transect analyses of visual observer data. Density = seals/km² ± Standard Error. ES=Eclipse Sound, MI=Milne Inlet, NB=Navy Board Inlet, WHB=Western Hudson Bay, WHBNS=Western Hudson Bay Near-Shore.

The effective number of breeders (N_b) within the Hudson Bay ringed seal population was compared over time with environmental data. Models used a variety of variables including snow depth, spring rain, date of freezer up. Spring rain, with a 5-year lag, and the date of fall freeze up, with a 7-year lag, were the most important predictors of N_b, and these variables explained most of the variation in the two models. At a lag of 5 years, the amount of spring rainfall negatively affected N_b (R^2= 0.387, T_9= -2.403, p= 0.040), and the date of fall freeze with a 7- year lag positively affected N_b (R^2= 0.608, T_9= 3.251, p= 0.010). When snow depth was analyzed separately, a 6-year lag of N_b relative to snow depth was the most likely model explaining variation in N_b, and snow depth was a significant predictor of N_b.

Regression analysis of the effective number of breeders (N_b) did not indicate a significant temporal trend (R^2= 0.0001, T_{25}=-0.119, p=0.906). Partial regressions of N_b, before and during the time aerial surveys were conducted, indicated a decline from 1983-1994 (R^2= 0.539, T_{10}=-3.52, p=0.006) before aerial surveys were flown, but during the time surveys were flown N_b increased (R^2=0.319, T_{13}=2.22, p=0.045). The number of seals counted from aerial surveys (Ns) ranged from 335.48 in 2013 to 2086.45 in 1995. The number of seals counted from aerial surveys did not change significantly over time (R^2=0.368, T_8=-2.12, p=0.067). We did not find a significant relationship between N_b and N_s (R^2=0.543, F_5=2.04, p=0.097) and there was no significant trend in N_b/N_s over time (R^2=0.676, T_5=2.41, p=0.061).

DISCUSSION

Bears

Early warning indicators for Arctic wildlife remain elusive for high trophic level species yet our program has made significant advances in using archived tissues as matrices for analysis. Our project was focussed on using archived samples and materials that are available from subsistence harvest or ongoing research/monitoring projects studying polar bears. A key step in the development of such biomarkers is the establishment of the core elements affecting variation and linking these to space-use patterns (i.e., telemetry data) and relevant environmental indices (e.g., sea ice cover duration). To understand how biomarkers respond to climate change, we need to have a fundamental understanding of the role of sex, age, reproductive status, and date of sampling. These analyses are ongoing and preliminary results suggest that the biomarkers all have great potential to provide warnings of change.

Whales

Narwhal movements revealed multiple fall migration patterns within the Eclipse Sound and Admiralty Inlet stocks. Narwhal in this dataset entered Baffin Bay later than narwhal tagged around a decade previously (Dietz et al. 2001, Heide-Jørgensen et al. 2002). Whether this is related to changes in ice extent needs to be further studied. Similarly timed movements of narwhal from the Eclipse Sound stock into Admiralty Inlet occurred across multiple years (Heide-Jørgensen et al. 2002) and therefore appear to constitute annual movement patterns for at least some portion of the Admiralty Inlet stock. Overall, we found that potential prey availability was more influential in habitat selection than sea ice structure. The predominantly available sea ice concentration within the wintering area is >95%, which likely accounts for why the model showed narwhal selecting this ice type. The model selection of sea ice concentration <35% is likely related to extensive narwhal movements recorded in 2010 that corresponded with a lower sea ice extent. These did not appear to be the main drivers for why narwhal were travelling to different areas. Instead it appears that bathymetry was the main variable influencing habitat selection. Surveys on main winter prey species indicate that Greenland halibut occur at highest densities at depths >800 m (Jørgensen 2011, Treble 2015). Narwhals conduct longer and deeper dives with increasing bathymetric depth (Laidre et al. 2004), and frequently conduct foraged-shaped dives between 800 m and >1400 m (Laidre et al. 2003, Watt et al. 2015). We feel that this indicates that narwhals may be avoiding bathymetric depths <1000 m and selecting bathymetry 1500-2000 m in relation to prey availability.

Narwhal diet shows strong variation in relation to seasonal migration and prey availability (Laidre and Heide-Jørgensen 2005). Shifts in prey abundance may have inevitably influenced narwhals both indirectly via reproduction and directly via diet. Reproductive rates of narwhals have been estimated by biologists through the examination of reproductive organs Narwhal diet has been relatively well studied at the population level using stomach contents (Finley and Gibb 1982, Laidre and Heide-Jørgensen 2005), and stable isotope and fatty acid analyses (Watt et al. 2013, Watt and Ferguson 2015). However, dietary variation among individuals within a population is still poorly understood. Understanding inter-individual variation in diet can give insight as to the potentially different impact of changing resource on varied groups of narwhals within a population. Thus, the current ongoing narwhal tusk analysis will provide a better understanding of narwhal diet and population dynamics in the Canadian Arctic.

Killer whales of the eastern Canadian Arctic prey on a variety of culturally and economically valuable marine mammal species including bowhead whales, beluga whales, narwhals, ringed seals, bearded seals and harp seals (Higdon et al. 2012). Climate change has led to decreases in the extent and duration of seasonal sea ice in the eastern Canadian Arctic (Stroeve et al. 2014), and killer whales may consequently undergo a range expansion, occupying more northerly latitudes for longer periods of time (Moore and Huntington 2008). This may result in increased predation on Arctic marine mammals (Higdon et al. 2012). Killer whales have historically been documented to influence ecosystems via top down processes (e.g. Estes et al. 1998) and accounting for the impacts of killer whale predation on prey populations of cultural and economic importance to Inuit is necessary for effective stock management. However, our limited understanding of the ecology of eastern Canadian Arctic killer whales makes it difficult to quantify their ecosystem impacts (COSEWIC 2008).

The bowhead biopsy samples collected in 2017 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 is then used to estimate the total local population size. An updated abundance estimate is anticipated in 2018-19. Using the aerial photos of bowhead whales collected in Cumberland Sound in 2016 and 2017, a photo ID catalogue is being developed. In time, this catalogue will allow for assessments of important life history traits and population demography including measures of body condition, growth rates, and calving intervals.

We have demonstrated that Cumberland Sound is an important summertime feeding area for Eastern Canada-West Greenland bowhead whales. Our co-located prey and dive data have shown that animals are exploiting shallow aggregations of lower quality temperate species (e.g., *C. finmarchicus*) and early-stage Arctic species (e.g., *C. glacialis*) and deeper concentrations of higher quality prey that is dominated by late-stage Arctic taxa (e.g., *C. hyperboreus* and *C. glacialis*). Consequently, bowheads employ a multi-depth foraging strategy that includes a diverse diet of Calanoid copepods. The results of this analysis will provide important insight regarding the feeding regime of bowhead whales under current environmental conditions to enable future analysis of how feeding conditions may be affected by climate change. These results demonstrate that Cumberland Sound is a summertime feeding habitat for a segment of the Eastern Canada-West Greenland bowhead whale population and that individuals employ a complex foraging strategy to meet their daily energy requirements.

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 as well as engage local participation. 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., 2013; Chambellant et al., 2012; Ferguson et al., 2017; Ferreira et al., 2011; Young and Ferguson, 2013; Young and Ferguson, 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.

Ringed seal foraging ecology around Baffin Island showed an overall decline of fish in the diet which is mainly driven by decreased presence of Arctic cod and snailfish, and increased consumption of invertebrates, mainly amphipods, euphausiids, and mysids. These stomach content results are consistent with other findings that the abundance of preferred prey, the endemic Arctic cod, has been declining, accompanied by a rise of the sub-Arctic forage fish, capelin, in many Arctic regions (Gaston et al. 2003, McNicholl et al. 2017). A distinction between the north and the south is the larger diversity of invertebrates consumed by seals in Pangnirtung as compared to northern Baffin Island.

Ringed and harp seals share similar resources during the time that they are co-occurring, suggesting that there is the potential for competition if conditions were such that resources were limited. The high isotopic niche overlap before the seals are sympatric could be due to similar foraging ecology and close genetic relatedness of ringed and harp seals in the area (Berta et al. 2006). It appears, however, that while both seals consume the same prey groups, the fish that harp seals consumed are both larger in quantity and in size compared to ringed seals, suggesting that resources are being selected differently (Wathne et al. 2000). This could mean that in resource-limited conditions, niche partitioning is possible.

The degree of individualization in diet consumption and pattern of dietary consistency will allow for a better understanding of ringed seal foraging in Hudson Bay. Ringed seals have been previously described as a generalist consumer that may switch their diet and foraging habits in relation to season and access to prey (Thiemann et al. 2007; Chambellant et al. 2012; Young and Ferguson 2013). There have been documented diet signature differences between age-classes and geographic locations (Hobson et al. 1996; Thiemann et al. 2007; Young et al. 2010). Recently, Yurkowski et al. (2016) revealed that total ringed seal niche width decreased with latitude, possibly because there was more ecological opportunity in the southern extent of the ringed seals range, however, this study was not able to assess within-individual diet consistency or variation because SI values were obtained from muscle and livers. Chronologically sampling along ringed seal vibrissae will allow for within-individual diet comparisons, and will reveal if individual ringed diet composition is consistent or variable over time. The growth rates of phocid seal vibrissae are unclear, but approximately two mm/week for harbour seals. Thus, vibrissae length for ringed seals ranged from 22 mm – 76 mm (data on file) representing up to 40 weeks of diet and can be used to determine within-indiviudual dietary variation. In addition to the multiple measures of diet for each individual, we have corresponding dive behaviour from satellite telemetry tags on the same individual that will be used to test the degree of individualization in ringed seals assessed by vibrissae SI biomarkers and dive patterns (i.e. frequency of benthic dives).

Infrared methods for conducting aerial surveys of ice seals allow for improved detection of animals, particularly under difficult sighting conditions. This results in a high probability of detection over a defined strip width, and meets the key assumption of strip transect analysis. The use of infrared imagery also requires fewer survey personnel, eliminating the need for large teams of observers while simplifying the process of data analysis and density estimation. These findings are consistent with other studies, which have tested infrared technology for surveying ringed seals on ice (Conn et al., 2014). As technology continues to develop, infrared surveys of ice seals can be conducted using unmanned aerial vehicles, reducing disturbance to animals and improving safety.

We implemented a genetic approach for monitoring trends in abundance of ringed seals. While the method we used is more precise when applied to smaller populations, with closed systems, our overall result of the ratio between N_b and N_s was consistent with estimates of isolated populations of ringed seals (*Pusa hispida saimensis*), harbour seals and New Zealand sea lion (*Phocarctos hookeri*), that have a relatively large distribution and population size (Andersen et al. 2011; Valtonen et al. 2014; Collins et al. 2016). However, we did not detect a positive relationship between our estimates of the effective number of breeders (N_b) and the number of seals counted in aerial surveys (N_s). We found that the amount of spring rainfall, dry snow depth, and the date of fall freezeup had an effect on N_b, while the date of fall freezeup was not an important predictor. There were lags between environmental variables and N_b of 5, 6, and 7 years for spring rainfall, snow depth, and the date of fall freezeup respectively.

Our results indicate that in western Hudson Bay, when lags are considered, increased spring rainfall negatively affects ringed seal N_b and that snow depth and the date of fall freezeup have positive relationships with N_b. The link between snow depth and recruitment has been established previously (Furgal et al. 1996; Ferguson et al. 2005; Iacozza and Ferguson 2014), and spring rainfall has been noted to affect survival by collapsing lairs during spring, which increases exposure to predators (Lydersen and Smith 1989) and harsh conditions (Kelly 2001). There is a lag between environmental variables and N_b because of the time it takes ringed seals to reach maturity and start contributing to N_b by breeding. Since ringed seal mortality is highest when they are young, environmental variables affect the survival of a given cohort. If environmental conditions are favourable and mortality is low, N_b will increase once they start breeding or vice-versa if conditions reduce juvenile survival. Over the length of our study N_b did not show a significant trend overall, although N_b appeared to decline in the 1990s and increase in the 2000s. The lower N_b in the 1990s corresponds to lower recruitment of ringed seals in western Hudson Bay in the 1990s, which was attributed to less snowfall, lower snow depth, and warmer temperatures in April and May (Ferguson et al. 2005). We did not observe a relationship between N_s estimates from aerial surveys and our genetic estimates of N_b, as we had hypothesized.

CONCLUSION

In conclusion, marine mammals are facing a number of challenges with ongoing climate change. The Arctic marine ecosystem in experiencing ongoing alterations as a whole, which is influencing marine mammal movement, habitat selection, foraging and diet composition, body condition and health. Through large network collaborations, we use a variety of research techniques and examination of large dataset using archived data to further understand how marine mammals are interacting with the environment and changing their behaviours.

Our polar bear research has made significant advances in the past year; numerous publications are moving to peer review and will set a new framework for monitoring of polar bears. Our focus on less invasive methods is a priority for northern communities and our research will make meaningful contributions in answering ecological questions. Our research program identifies the mechanisms associated with polar bear population change over time to assess and predicts the effects of anthropogenic global climate change. Using archived hair, claw, blood, and premolar teeth sampled over the past 40 years across the Canadian Arctic we have processed various biomarkers to assess their utility to detect change.

We better understand cetacean habitat selection and distribution in the Arctic. Narwhals selected deep areas along the shelf break that likely support relatively higher prey densities. This would indicate that as the ice structure itself changes, there likely will be little direct impact on narwhal as they are adapted to multiple ice types. However indirect impacts in relation to changing prey density and location are possible. These impacts are focusing on changes of the sea ice structure within the ice pack and not the potential impacts on declining sea ice extent. Beluga habitat selection in Cumberland Sound can be successfully determined through non-invasive passive acoustic monitoring and analyzed with automated detectors, improving our ability to process large datasets archived by hydrophone recorders.

We have demonstrated that Cumberland Sound is an important summertime feeding area for Eastern Canada-West Greenland bowhead whales. Our co-located prey and dive data have shown that animals are exploiting shallow aggregations of lower quality temperate species and early-stage Arctic species and deeper concentrations of higher quality prey that is dominated by late-stage Arctic taxa. Consequently, bowheads employ a multi-depth foraging strategy that includes a diverse diet of Calanoid copepods.

Understanding the feeding ecology of ringed seals as well as tracking changes over time will help wildlife managers better understand the evolving dynamics of the Arctic food web and determine potential impacts on species at higher trophic levels. Most importantly, our research will help in addressing Inuit concerns regarding the use of local Inuit knowledge as a valuable component to scientific research.

Using techniques to study ringed seal effective population sizes are important tools as these methods indicate that aerial surveys may not represent the true number of ringed seals in the survey area. It also indicated that environmental stochasticity might drive changes in abundance of ringed seals. Generally, when conditions are favourable, juvenile recruitment is higher leading to higher abundances. Specifically, we found that greater snow depth leads to higher effective population size while greater spring rainfall leads to lower effective population size.

Future climatic conditions are expected to continue to alter the Arctic ecosystem, thus the ecology of marine mammal adaption to sea ice habitat as an integral part of the system will be affected. Altered population dynamics, abundance trends, migration patterns and new prey and predators are likely results. Expansion of ecological investigation and wildlife health baseline studies concurrent with existing demographic research on the distribution and abundance of marine mammals are crucial for local management and subsistence food monitoring programs. The "Innovative Research on Monitoring Marine Mammals to Mitigate Impacts of Changing Arctic" research group has demonstrated the need for more research to ensure conservation success of Arctic marine mammals.

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REFERENECES

Chambellant, M., Stirling, I. and Ferguson, S.H. 2013. Temporal variation in western Hudson Bay ringed seal *Phoca hispida* diet in relation to environment. Mar. Ecol. Pro. Ser. 481, 269-287.

Chambellant, M., Stirling, I., Gough, W.A. and Ferguson, S.H. 2012. Temporal variations in Hudson Bay ringed seal (*Phoca hispida*) life-history parameters in relation to environment. J. Mammal. 93, 267-281.

Conn, P.B., Ver Hoef, J.M., McClintock, B.T., Moreland, E.E., London, J.M., Cameron, M.F., Dahle, S.P. and Boveng, P.L. 2014. Estimating multispecies abundance using automated detection systems: ice-associated seals in the Bering Sea. Meth. Ecol. Evol. 5, 1280-1293.

COSEWIC. 2008. COSEWIC assessment and update status report on the Killer Whale *Orcinus orca*, Southern Resident population, Northern Resident population, West Coast Transient population, Offshore population and Northwest Atlantic/Eastern Arctic population, in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa, Canada. viii + 65 pp.

Dietz, R., M. P. Heide-Jørgensen, P. Richard, J. Orr, K. L. Laidre, and H. C. Schmidt 2008. Movements of narwhals (*Monodon monoceros*) from Admiralty Inlet monitored by satellite telemetry. Polar Biol. 31(11), 1295-1306.

Estes, J.A., Tinker, M.T., Williams, T.M. and Doak, D.F. 1998. Killer Whale Predation on Sea Otters Linking Oceanic and Nearshore Ecosystems. Science, v.282, no.5388. 473-476.

Ferguson, S. H., Stirling, I., and McLoughlin, P. 2005. Climate change and ringed seal (*Phoca hispida*) recruitment in western Hudson Bay. Mar. Mam. Sci. 21(1):121-135.

Ferguson, S.H., Young, B.G., Yurkowski, D.J., Anderson, R., Willing, C. and Nielsen, O. 2017. Demographic, ecological, and physiological responses of ringed seals to an abrupt decline in sea ice availability. PeerJ, 5:e2957; DOI 10.7717/peerj.2957.

Ferreira, E.O., Loseto, L.L. and Ferguson, S.H. 2011. Assessment of claw growth-layer groups from ringed seals (*Pusa hispida*) as biomonitors of inter-and intra-annual Hg, $\delta^{15}N$, and $\delta^{13}C$ variation. Can. J. Zool. 89, 774-784.

Finley, K.J., and Gibb, E.J. 1982. Summer diet of the narwhal (*Monodon monoceros*) in Pond Inlet, northern Baffin Island. Can. J. Zool. 60: 3353–3363. doi:10.1139/z82-424.

Gaston, A.J., Woo, K., and Hipfner, J.M. 2003. Trends in forage fish populations in Northern Hudson Bay since 1981, as determined from the diet of nestling thick-billed Murres *Uria lomvia*. Arctic 56: 227–233.

Heide-Jørgensen, M.P. 2015. Life history parameters of narwhals (*Monodon monoceros*) from Greenland. J. Mammal. 96: 866–879. doi:10.1093/jmammal/gyv110.

Heide-Jørgensen, M. P., K. L. Laidre, and P. R. Richard. 2002. Autumn movements, home ranges, and winter density of narwhals (*Monodon monoceros*) tagged in Tremblay Sound, Baffin Island. Polar Biol. 25, 331-341.

Higdon, J.W., Hauser, D.D.W. and Ferguson, S.H. 2012. Killer whales (*Orcinus orca*) in the Canadian Arctic: Distribution, prey items, group sizes, and seasonality. Mar. Mamm. Sci. v.28, no.2. 93-109.

Hobson, K. A., Schell, D. M., Renouf, D., and Noseworthy, E. 1996. Stable carbon and nitrogen isotopic fractionation between diet and tissues of captive seals: implications for dietary reconstructions involving marine mammals. Can. J. Fisher. Aquat. Sci. 53(3): 528-533.

Iacozza, J., & Ferguson, S. H. 2014. Spatio-temporal variability of snow over sea ice in western Hudson Bay, with reference to ringed seal pup survival. Pol. Biol,.37(6): 817-832.

Jørgensen, O. A. 2011. Bottom trawl survey in Baffin Bay, NAFO Divisions 1A, 2010. Technical Report NAFO SCR Doc. 11/010, Northwest Atlantic Fisheries Organization.

Kelly, J. F. 2001. Stable isotopes of carbon and nitrogen in the study of avian and mammalian trophic ecology. Can. J. Zool. 78(1): 1-27.

Laidre, K. L., Heide-Jørgensen, M. P., Dietz, R., Hobbs, R. C., and Jørgensen R. C. 2003. Deep-diving by narwhals *Monodon monoceros*: Differences in foraging behavior between wintering areas? Mar. Ecol. Prog. Ser. 261,269-281.

Laidre, K. L., Heide-Jørgensen, M. P., Logdson, M. L., Hobbs, R. C., Heagerty, R. C., Dietz, R., Jørgensen, O. A., and Treble O. A. 2004. Seasonal narwhal habitat associations in the high Arctic. Mar. Biol. 145, 821-831.

Laidre, K.L., and Heide-Jørgensen, M.P. 2005. Arctic sea ice trends and narwhal vulnerability. Biol. Conserv. 121: 509–517. doi:10.1016/j.biocon.2004.06.003.

Laidre, K.L., Stirling, I., Lowry, L.F., Wiig, Ø., Heide-Jørgensen, M.P., and Ferguson, S.H. 2008. Quanifying the sensitivity of Arctic marine mammals to climate-induced habitat change. Ecol. Appl. 18: S97–S125. doi:10.1890/06-0546.1.

Lydersen, C., and Smith, T. G. 1989. Avian predation on ringed seal *Phoca hispida* pups. Pol. Biol. 9(8): 489-490.

McNicholl, D.G., Wolki, B., and Ostertag, S. 2017. Traditional ecological knowledge and local observations of capelin (*Mallotus villosus*) in Darnley Bay, NT. Can. Manuscr. Rep. Fish. Aquat. Sci. 3144: vi + 20p.

Moore, S. E. and Huntington, H.P. 2008. Arctic marine mammals and climate change: Impacts and resilience. Ecol. Appl. v18. 157-165.

Stroeve, J.C., Markus, T., Boisvert, L., Miller, J. and Barrett, A. 2014. Changes in Arctic melt season and implications for sea ice loss. Geophy. Res. Let. v.41, no.4. 1216-1225.

Treble, M. A. 2015. Report on Greenland halibut caught during the 2014 trawl survey in Divisions 0A and 0B. Technical Report NAFO SCR Doc. 15/030, Northwest Atlantic Fisheries Organization.

Thiemann, G. W., Iverson, S. J., and Stirling, I. 2007. Variability in the blubber fatty acid composition of ringed seals (*Phoca hispida)* across the Canadian Arctic. Mar. Mam. Sci., 23(2), 241-261.

Watt, C. A., J. R. Orr, M. P. Heide-Jørgensen, N. H. Nielsen, and S. H. Ferguson. 2015. Differences in dive behaviour among the world's three narwhal *Monodon monoceros* populations correspond with dietary differences. Mar. Ecol. Prog. Ser. 525, 273-285.

Watt, C.A., and Ferguson, S.H. 2015. Fatty acids and stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) reveal temporal changes in narwhal (*Monodon monoceros*) diet linked to migration patterns. Mar. Mammal Sci. 31: 21–44. doi:10.1111/mms.12131.

PUBLICATIONS

Auger-Méthé, M., Albertsen, C.M., Jonsen, I.D., Derocher, A.E., Lidgard, D.C., Studholme, K.R., Bowen, W.D., Crossin, G.T. and Mills Flemming, J. 2017. Spatiotemporal modelling of marine movement data using Template Model Builder (TMB). Marine Ecology Progress Series, v.565, 237-249.

Bechshoft, T., Derocher, A.E., Viengkone, M., Routti, H., Aars, J., Letcher, R.J., Dietz, R., Sonne, C., Jenssen, B.M., Richardson, E. and Lunn, N.J. 2018. On the integration of ecological and physiological variables in polar bear toxicology research: a systematic review. Environmental Reviews (In Press).

Breed, G.A., Matthews, C.J.D., Marcoux, M., Higdon, J.W., LeBlanc, B., Petersen, S.D., Orr, J., Reinhart, N.R. and Ferguson, S.H. 2017. Sustained disruption of narwhal habitat use and behavior in the presence of Arctic killer whales. Proceedings of the National Academy of Sciences, v.114, 2628-2633.

Brown, T.A., Chrystal, E., Ferguson, S.H., Yurkowski, D.J., Watt, C., Hussey, N.E., Kelley, T.C. and Belt, S.T. 2017. Coupled changes between the H-Print biomarker and $\delta^{15}N$ indicates a variable sea ice carbon contribution to the diet of Cumberland Sound beluga whales. Limnology and Oceanography, v.62, 1606-1619.

Brown, T.A., Galicia, M.P., Thiemann, G.W., Belt, S.T., Yurkowski, D.J. and Dyck, M.G. High contributions of sea ice derived carbon in polar bear (*Ursus maritimus*) tissue. PLoS ONE (Accepted).

Castro de la Guardia, L., Myers, P.G., Derocher, A.E., Lunn, N.J. and Terwisscha van Scheltinga, A.D. 2017. Sea ice cycle in western Hudson Bay, Canada, from a polar bear perspective. Marine Ecology Progress Series, v.564, 225-233.

Davidson, E., Ferguson, S.H., Hidgon, J. and Treble, M.A. Distribution and habitat associations of sperm whales (*Physeter macrocephalus*) and northern bottlenose whales (*Hyperdoon ampullatus*) in Baffin Bay-Davis Strait. Polar Biology (Submitted).

Dey, C.J., Yurkowski, D.J., Schuster, R., Shiffman, D. and Bittick, S.J. Scientific research on Arctic vertebrates is not addressing conservation uncertainty. Conservation Letters (In Review).

Escajeda, E., Laidre, K.L., Born, E.W., Wiig, Ø., Atkinson, S., Dyck, M., Ferguson, S.H. and Lunn, N.J. 2017. Identifying shifts in maternity den phenology and habitat characteristics of polar bears (*Ursus maritimus*) in Baffin Bay and Kane Basin. Polar Biology, v41, 87-100.

Ferguson, S.H., Young, B.G., Yurkowski, D.J., Anderson, R., Willing, C. and Nielsen, O. 2017. Demographic, ecological, and physiological responses of ringed seals to an abrupt decline in sea ice availability. PeerJ, v.5, e2957.

Ferguson, S.H., Zhu, X., Young, B.G., Yurkowski, D.J., Thiemann, G.W., Fisk, A.T. and Muir, D.C.G. Geographic variation in ringed seal growth and body size. Canadian Journal of Zoology (Accepted).

Fisk, A.T., Landry, J.L., Yurkowski, D.J., Hussey, N.E., Dick, T., Crawford, R. and Kessel, S.T. Diet Specialization and Habitat Coupling of a Common Benthic Fish, Shorthorn Sculpin (*Myoxocephalus scorpius*) in the High Arctic. Polar Biology (In Review).

Florko, K.R.N., Bernhardt, W., Breiter, C.J.C., Ferguson, S.H., Hainstock, M., Young, B.G. and Petersen, S.D. 2018. Decreasing sea ice conditions in western Hudson Bay and an increase in abundance of harbour seals (*Phoca vitulina*) in the Churchill River. Polar Biology (In Press).

Fortune, S., Koski, W., Higdon, J., Trites, A., Baumgartner, M. and Ferguson, S.H. 2017. Evidence of molting and the function of "rock-nosing" behavior in bowhead whales in the eastern Canadian Arctic. PLoS One, v.12, e0186156.

Houde, M., Wang, X., Ferguson, S.H., Gagnon, P., Brown, T.M., Tanabe, S., Kunito, T., Kwan, M. and Muir, D.C.G. 2017. Spatial and temporal trends of alternative flame retardants and polybrominated diphenyl ethers in ringed seals (*Phoca hispida*) across the Canadian Arctic. Environmental Pollution, v.223, 266-276.

Johnson, A.C., Pongracz, J.D. and Derocher, A.E. 2017. Long distance movement of a female polar bear from Canada to Russia. Arctic, v.70, 121-128.

Kenyon, K. 2017. Movement Patterns and Winter Habitat Use of Narwhal (*Monodon Monoceros*) in the Eastern Canadian Arctic. MSc. Thesis, University of Manitoba, MB.

Kenyon, K., Yurkowski, D.J., Orr, J., Barber, D. and Ferguson, S.H. Baffin Bay narwhal (*Monodon monoceros*) select bathymetry over sea ice during winter. Polar Biology (In Review).

Kessel, S.T., Alhasan, N., Yurkowski, D.J., Walter, R.P., Klaus, R., Chekchak, T., Hill, G. and Hussey, N.E. Spatial use of reef Manta rays (*Manta alfredi*) relative to marine reserve boundaries and a proposed large-scale island development in Sudan's Red Sea. PLoS ONE (Accepted).

Lefort, K.J., Matthews, C.J.D. and Ferguson, S.H. 2017. Orcas of the Canadian Arctic: August 2017 Research in Arctic Bay, Nunavut. Internal Field Report, Department of Fisheries and Oceans Canada, Winnipeg, MB.

McCloskey, M., Yurkowski, D.J. and Semeniuk, C.A.D. Validating fin tissue as a non-lethal tissue for stable isotope analysis of yellow perch (*Perca flavescens*). Isotopes in Environmental and Health Studies (Accepted).

Nguyen, L., Pilfold, N.W., Derocher, A.E., Stirling, I., Bohart, A.M. and Richardson, E. 2017. Ringed seal (*Pusa hispida*) tooth annuli as an index of reproduction in the Beaufort Sea. Ecological Indicators, v.77, 286-292.

Pedro, S., Fisk, A., Tomy, G., Ferguson, S.H., Hussey, N., Kessel, S.T. and McKinney, M.A. 2017. Mercury and persistent organic pollutants in native and invading forage species of the Canadian Arctic: Consequences for food web dynamics. Environmental Pollution, v.229, 229-240

Pilfold, N.W., McCall, A., Derocher, A.E., Lunn, N.J. and Richardson, E. 2017. Migratory response of polar bears to sea ice loss: to swim or not to swim. Ecography, v.40, 189-199.

Pomerleau, C., Heide-Jørgensen, M.P., Ferguson, S.H., Stern, H., Høyer, J.L. and Stern, G.A. 2017. Reconstructing variability in West Greenland ocean biogeochemistry and bowhead whale (*Balaena mysticetus*) food web structure using amino acid isotope ratios. Polar Biology (In Press).

Rode, K.D., Wilson, R.R., Douglas, D.C., Muhlenbruch, V., Atwood, T.C., Regehr, E.V., Richardson, E.S., Pilfold, N.W., Derocher, A.E., Durner, G.M., Stirling, I., Amstrup, S.C., St Martin, M., Pagano, A.M. and Simac, K. 2018. Spring fasting behavior in a marine apex predator provides an index of ecosystem productivity. Global Change Biology, v.24, 410-423.

Sciullo, L., Thiemann, G.W., Lunn, N.J. and Ferguson, S.H. 2017. Intraspecific and temporal variability in the diet composition of female polar bears in a seasonal sea ice regime. Arctic Science (In Press).

Smith, A.J., Higdon, J.W., Richard, P., Orr, J., Bernhardt, W. and Ferguson, S.H. 2017. Beluga whale summer habitat associations in the Nelson River Estuary, western Hudson Bay, Canada. PloSONE, v.12, e0181045.

Togunov, R.R., Derocher, A.E. and Lunn, N.J. 2017. Windscapes and olfactory foraging in a large carnivore. Scientific Reports, v.7, 46332.

Watt, C.A., Orr, J.R. and Ferguson, S.H. 2017. Spatial distribution of narwhal (*Monodon monoceros*) diving for Canadian populations helps identify important seasonal foraging areas. Canadian Journal of Zoology, v.95, 41-50

Westdal, K.H., Davies, J., MacPherson, A., Orr, J. and Ferguson, S.H. 2016. Behavioural changes in belugas (*Delphinapterus leucas*) during a killer whale (Orcinus orca) attack in southwest Hudson Bay. Canadian Field-Naturalist, v.130, 315-319.

Yee, M., Reimer, J., Lunn, N.J., Togunov, R.R., Pilfold, N.W., McCall, A.G. and Derocher, A.E. 2017. Polar bear (*Ursus maritimus*) migration from maternal dens in western Hudson Bay. Arctic, v.70, 319-327.

Young, B.G., Yurkowski, D.J., Dunn, B. and Ferguson, S.H. Comparing Infrared Imagery to Traditional Methods for Estimating Ringed Seal Density. Wildlife Society Bulletin (In Review).

Yurkowski, D.J., Auger-Méthé, M., Mallory, M.L., Wong, S.N.P., Gilchrist, H.G., Derocher, A.E., Richardson, E., Lunn, N.J., Hussey, N.E., Marcoux, M., Togunov, R., Fisk, A.T., Harwood, L.A., Dietz, R., Rosing-Asvid, A., Born, E.W., Mosbech, A., Fort, J., Grémillet, D., Loseto, L., Richard, P.R., Iacozza, J., Jean-Gagnon, F., Brown, T.M., Westdal, K.H., Orr, J., LeBlanc, B., Hedges, K.J., Treble, M.A., Kessel, S.T., Blanchfield, P.J., Davis, S., Maftei, M., Spencer, N., McFarlane-Tranquilla, C.L., Montevecchi, W.A., Bartzen, B., Dickson, D.L., Anderson, C. and Ferguson, S.H. Abundance and species diversity hotspots of tracked marine predators across the North American Arctic. Diversity and Distributions (Submitted).

Yurkowski, D.J., Hussey, A.J., Hussey, N.E. and Fisk, A.T. 2017. Effects of decomposition on carbon and nitrogen stable isotope values of muscle tissue of varying lipid content from three aquatic vertebrate species. Rapid Communications in Mass Spectrometry, v.31, 389-395.

Yurkowski, D.J., Hussey, N.E., Ferguson, S.H. and Fisk, A.T. A temporal shift in prey species availability decreases trophic diversity among a predator assemblage in a changing Arctic. Royal Society Open Science (In Review).

Yurkowski, D.J., Hussey, N.E., Fisk, A.T., Imrie, K.L., Tallman, R.F. and Ferguson, S.H. Temporal shifts of forage fish availability decrease intraguild predation pressure between beluga whales and Greenland halibut in a warming Arctic. Biology Letters (Accepted).


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

Project Team

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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

Preliminary results from this project have revealed that bacteria in Canada's Arctic Ocean are 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 appears to be possible, but results have been difficult to reproduce, and due to the slow nature of anaerobic metabolism (i.e. long experiments) this 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 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*, as well as the RV *Martin Bergmann*, and the project involves collaborations with other scientists in Canada, the United States and the EU.

More broadly, a key message we wish to convey is that ArcticNet's investment in *The Potential for Natural Oil Spill Biodegradation by Microorganisms in Canada's Arctic Marine Environment* has been a catalyst for additional funding in the area of marine oil spill biodegradation, especially in the Arctic. The Calgary group has led other successful proposals, including large Genome Canada and NSERC (SPG) projects that are currently running and are continuing past the end date of the initial ArcticNet grant that gave this research line its start, back in early 2015. The funding, and more importantly the network, provided through ArcticNet established a necessary foundation to launch larger programs. These larger programs have enabled enhanced stakeholder interactions and research capacity. These valuable stakeholder and end user interactions has led to the concept of "monitored natural attenuation" as a legitimate oil spill response strategy, which is critical to lend credibility and accountability in a spill response scenario. This, and other developments of this area of research, will be an important legacy of this project.

RESEARCH OBJECTIVES

The overarching objective of the ArcticNet project was 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

Thanks to additional funding from a new Genome Canada project, GENICE, our team has continued to engage with important stakeholders including northern communities and different levels of government. During 2017-2018 GENICE hosted two workshops:

1. An end-user engagement meeting hosted at the University of Manitoba with the Canadian Coast Guard and members of the ArcticNet and GENICE research teams. Discussions around hydrocarbon contaminants and areas of spill response needs helped inform research direction and experimental design.
2. A Law and Policy workshop at Dalhousie University reviewed aspects of oil spills in the Arctic marine environment. The workshop was hosted at the Faculty of Law and solicited input from Law Professors and other experts, as well as from mayors Mike Spence (Churchill) and Simionie Sammurtok (Chesterfield Inlet).

Conferences presentations and posters:

1. Nutrient Amended Biodegradation of Hydrocarbon Contamination along Canada's Labrador Coast. Sean Murphy, ArcticNet 2017 International Arctic Change Conference, Quebec City, QC, December 11-15, 2017. Oral presentation and poster presentation. Awarded 1st place in the marine sciences division of the graduate student poster competition.
2. Nutrient Amended Biodegradation of Hydrocarbon Contamination along Canada's Labrador Coast. Sean Murphy, Gulf of Mexico Oil Spill and Ecosystem Conference, New Orleans, Louisiana, February 5-8, 2018. Oral presentation and poster presentation.

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 210Pb and ^{137}Cs were counted in sediment core sections at the Environmental Radiochemistry Laboratory (ERL) at the 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 the Centre for Earth Observation Science, 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 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

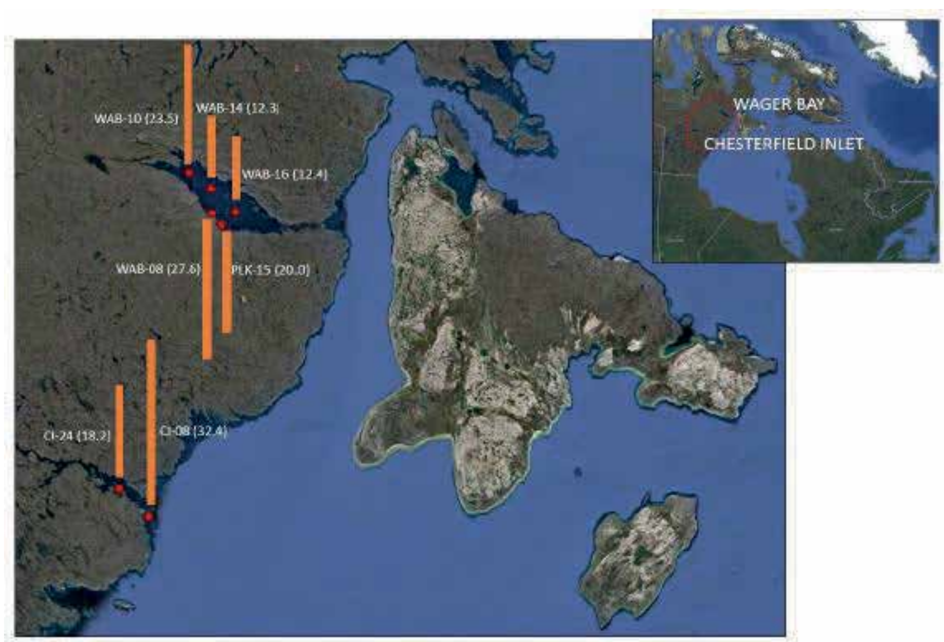

Figure 1. Sediment core locations near Chesterfield Inlet and Wager Bay, NU, sampled in 2016. Height of bars shows total concentrations of polycyclic aromatic hydrocarbons (PAHs) in top 2-cm sections of the cores. Because of intensified shipping activities and thus potential for future oil spills, this region will be a focus of future geomicrobiological studies to establish baselines using microbial diversity metrics. An expedition dedicated to this purpose aboard the new research vessel William Kennedy (purchased as part of the Manitoba-Calgary CFI collaboration Churchill Marine Observatory) is being considered for summer 2018.

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 (e.g. 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

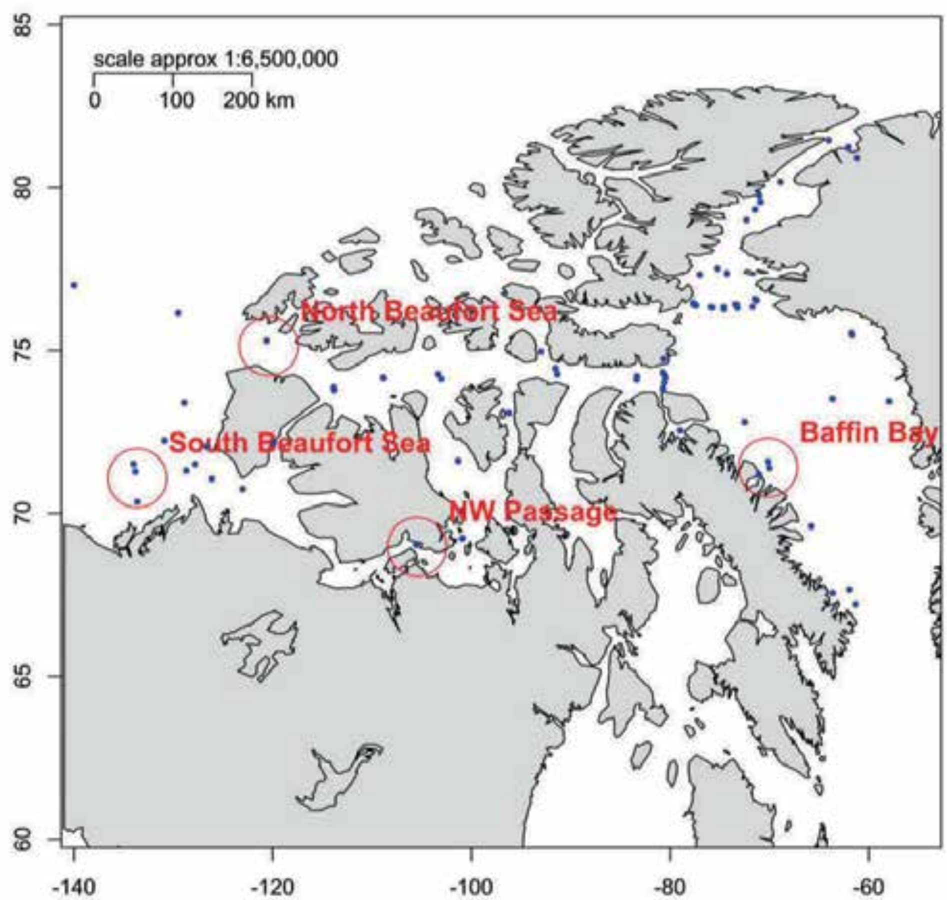

Figure 2. Sediment and water sampling sites displayed for the 2013-2017 CCGS Amundsen expeditions (blue dots), and the 4 areas targeted for hydrocarbon biodegradation incubation experiments (red circles) referred to in the text. Ice cores were also collected from the North Beaufort Sea area in 2016, and from the Cambridge Bay region (red circle "NW Passage") in 2017. RV Martin Bergmann expeditions in 2016 and 2017 involved high-density sampling in the same NW Passage area.

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, as well as at room temperature in some cases (to promote 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 Qiagen (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 AN projects and investigators (e.g. Evan Edinger), however problems encountered with the ROV prevented seabed sampling at hydrocarbon seeps.

An even more elaborate plan was put together for 2017 sampling at the Scott Inlet during the *Amundsen* Leg 2B using the SuMo ROV, however this ended up being cancelled due to ice cover. A joint application for ship time (NSERC STAC) was submitted in August 2017 led by Prof. Edinger and other ArcticNet Network Investigators. This STAC application was successful, so there will be attempts to sample at Scott Inlet again during the 2018 *Amundsen* Leg 2c. Analyses of these samples will be conducted within the Genome Canada GENICE project.

Other sampling expeditions were also cancelled in 2017 (*Amundsen* 2017 BaySys expedition in Hudson Bay; *White Diamond* expedition in Hudson Bay in October 2017), which impacted acquisition of targeted samples.

RESULTS

Geochemistry Results & Discussion

Modelling of radioisotope data in cores from Scott Inlet (a known hydrocarbon seep) 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 upwardly migrating hydrocarbons. Thus, low hydrocarbon concentrations may be expected and it is possible that these sediments might not offer a good model system for studying natural hydrocarbon biodegradation potential, if this is the case.

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 (i.e., a 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 light crude oil 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 5-7). 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' or using the more recent DADA2 pipeline for assessing single nucleotide amplicon sequence variants). Sediments from the Gulf of Mexico, provided by US project partners, will allow further testing of different metabolic capabilities in these different locations.

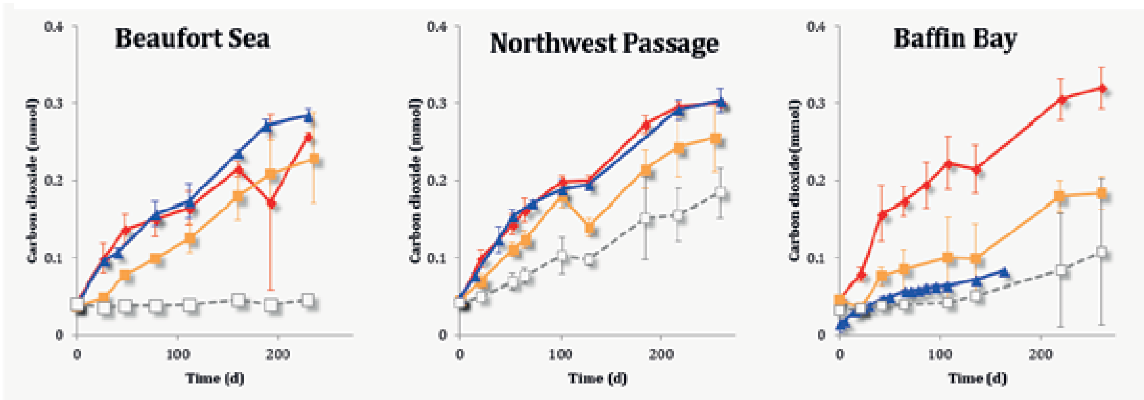

Figure 3. Enhanced microbial respiration (production of carbon dioxide) in Arctic marine sediment microcosms amended with 0.1% (v/v) diesel (blue triangles), bunker fuel (orange squares), or crude oil (red diamonds) at 4°C relative to unamended controls (grey squares). Error bars represent standard deviation across triplicate incubations for each condition. This response is indicative of hydrocarbon biodegradation by cold-adapted sediment microbial communities. The similar rates overall are likely due to the presence of considerable n-alkanes in all three mixtures, including the bunker fuel.

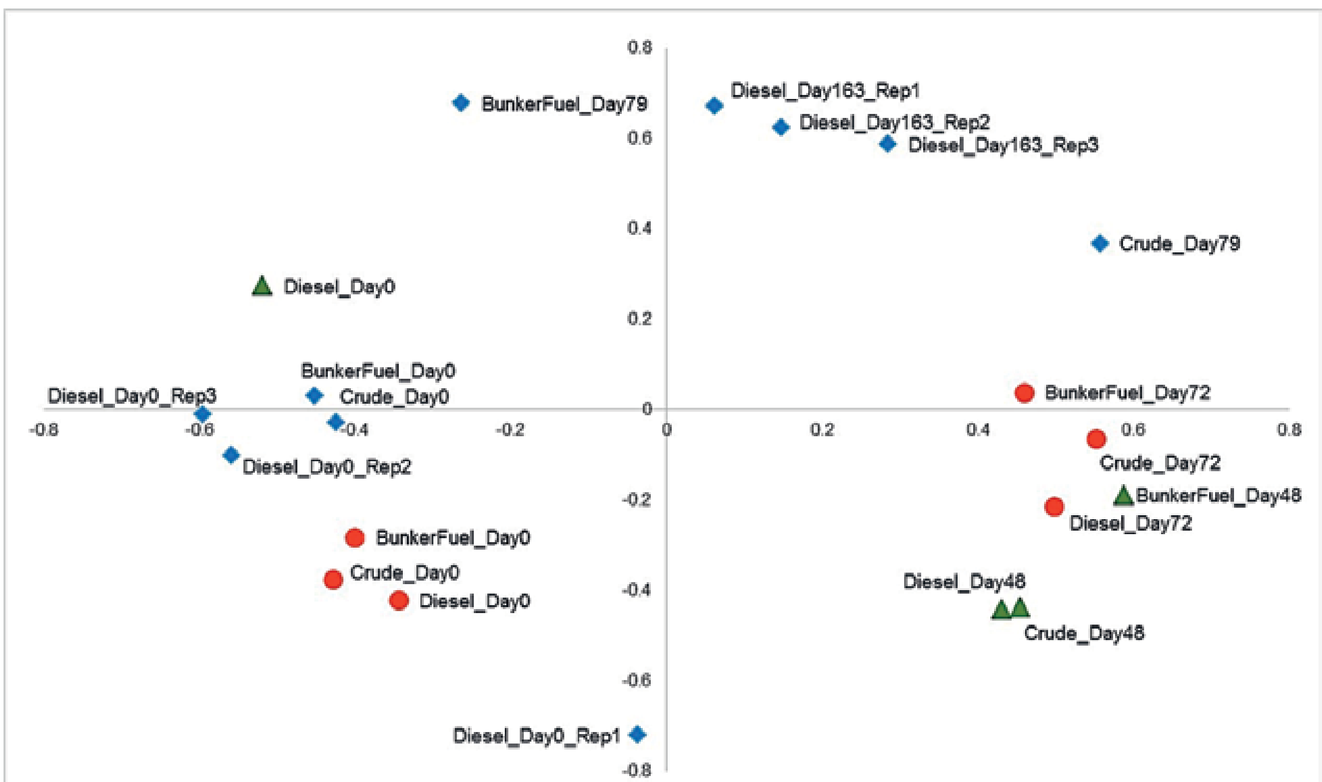

Figure 4. Non-metric multidimensional scaling of aerobic hydrocarbon biodegradation incubation 16S rRNA gene libraries (rarefied reads, Yue & Clayton Theta dissimilarity calculator; Stress: 0.242463, R-Squared: 0.743223). NW Passage (red circles), Beaufort Sea (green triangles), and Baffin Bay (blue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

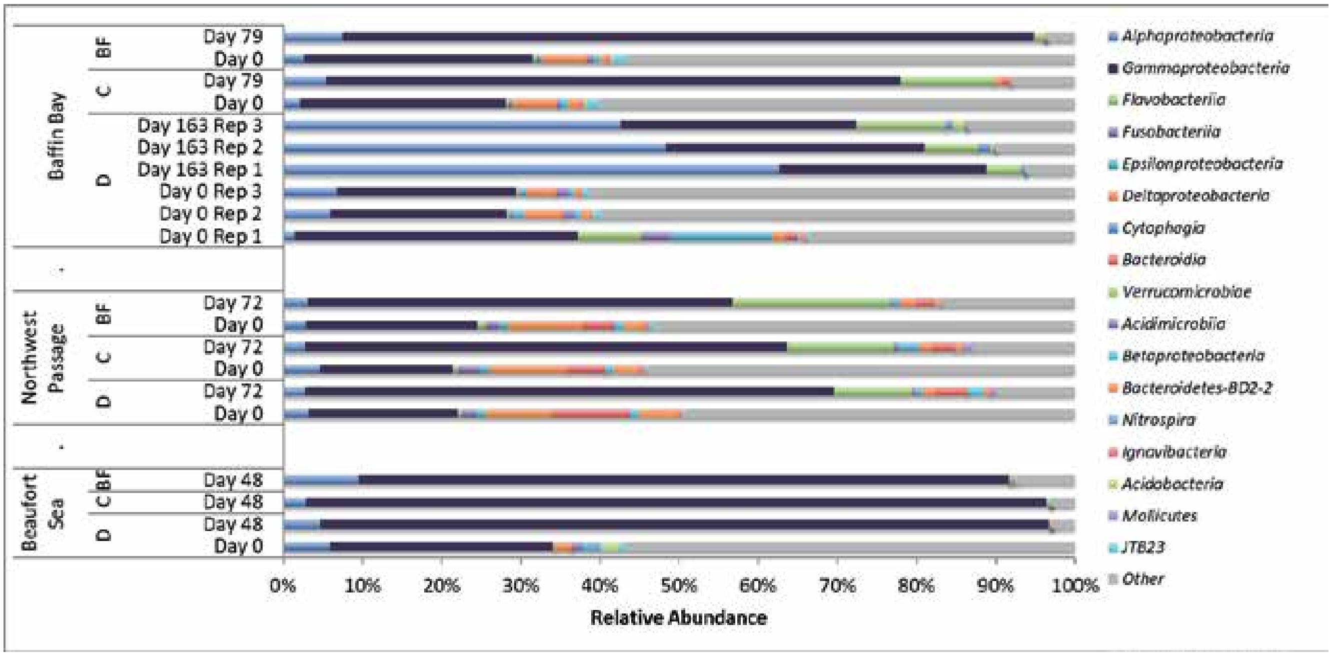

Figure 5. Illumina MiSeq 16S rRNA gene biodiversity libraries were prepared for Baffin Bay, Northwest Passage, and Beaufort Sea sediment microcosms amended with different contaminants (0.1% v/v diesel, bunker fuel, or crude oil) and subsampled for up to 163 days of incubation at 4°C. With the exception of Baffin Bay sediments incubated with diesel, hydrocarbon degradation incubations showed enrichments of Gammaproteobacterial Alcanivorax, Perlucidibaca, Cycloclasticus, and Oleispira spp. (cf. Figure 7). The Baffin Bay sediments incubated with diesel, which showed less carbon dioxide production compared to all other incubations (see Figure 3), exhibited enrichment of Alphaproteobacterial Sphingorhabdus and Hyphomonas spp. as well as Gammaproteobacterial Pseudomonas and Colwellia spp. (cf. Figure 6).

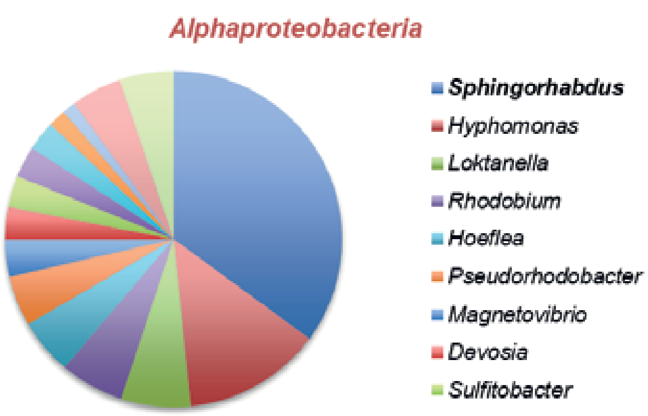

Figure 6. Sphingorhabdus spp. were the dominant Alphaproteobacteria enriched in Baffin Bay (Scott Inlet) sediment from station PCBC2 in the presence of diesel incubated at 4°C. Proportions shown are the mean relative sequence abundance values from triplicate 16S rRNA gene amplicon libraries.

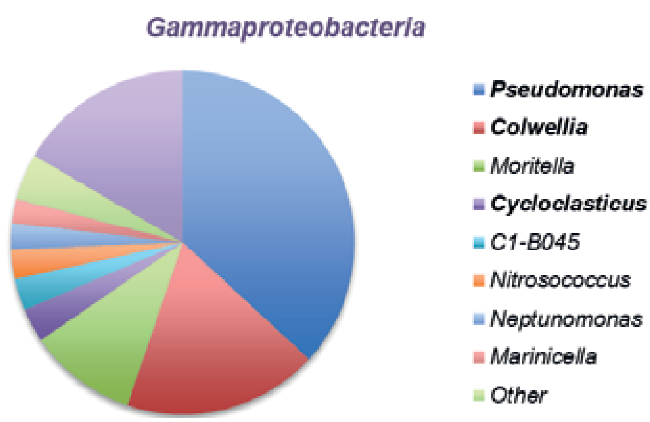

Figure 7. Pseudomonas, Colwellia, and Cycloclasticus spp. were the dominant Gammaproteobacteria enriched in the presence of diesel in Baffin Bay (Scott Inlet) sediment from station PCBC2 incubated at 4°C. These lineages include well-known hydrocarbon degraders from other low temperature marine habitats, including the Gulf of Mexico. Proportions shown are the mean relative abundance values from triplicate 16S rRNA gene amplicon libraries.

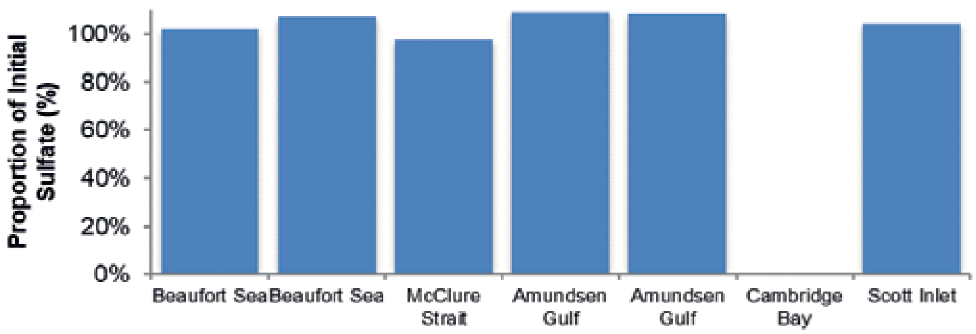

Figure 8. Eight-week incubations of seven different marine sediments under anoxic conditions in the presence of diesel only gave rise to sulphate consumption in Cambridge Bay sediments (ArcticNet station 314). For these triplicate incubations sulphate was completely consumed after 8 weeks, suggesting anaerobic hydrocarbon biodegradation potential may be high in this region. Each bar reports the mean value from triplicate incubations.

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 8 weeks of incubation at 4°C. These microcosms turned black (indicative of sulphate reduction, i.e., produced sulphide reacted with iron oxides in the sediment to precipitate FeS; Figure 9). FeS production represents an additional line of evidence for the activity of cold-adapted sulphate-reducing bacteria (SRB) enriched 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 8).

For the positive NW Passage result, further investigation using DNA sequence analysis revealed

Figure 9. 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. Figure 8) were similar in appearance to the controls (not shown).

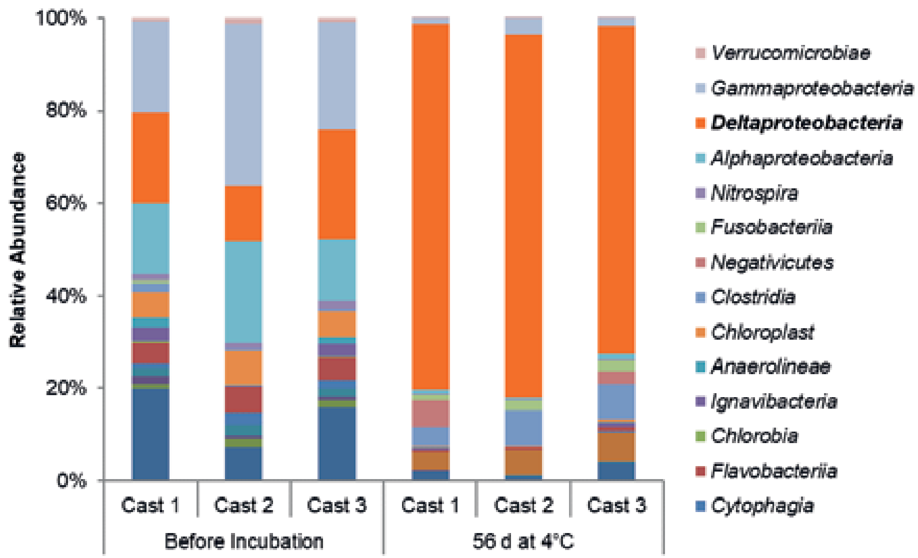

Figure 10. Illumina MiSeq 16S rRNA gene amplicon libraries were prepared for triplicate microcosms prepared using sediment obtained from separate, triplicate box core casts at station 314 near Cambridge Bay. The libraries indicate enrichment of cold-adapted Deltaproteobacteria after 56 days under cold 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).

significant enrichment of two Deltaproteobacterial genera, *Desulfofrigus* (enriched to 40% of the total microcosm community) and *Desulfotalea* (enriched to 25%) as shown in Figure 10. 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 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 11) 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 is needed to further assess this result.

Oscar Montoya's research investigated the biodegradation of polycyclic aromatic hydrocarbons (PAHs) under aerobic and anaerobic conditions. Oscar performed some incubations with sediment samples from the Beaufort Sea sampled from the *Amundsen* in 2015, as well as using enrichment cultures from other hydrocarbon impacted environments. Under anaerobic conditions, the results were mostly inconclusive owing in part to the very slow nature of methanogenic hydrocarbon biodegradation, in support of hypothesis 2 above. Oscar successfully defended his M.Sc. thesis in October 2017.

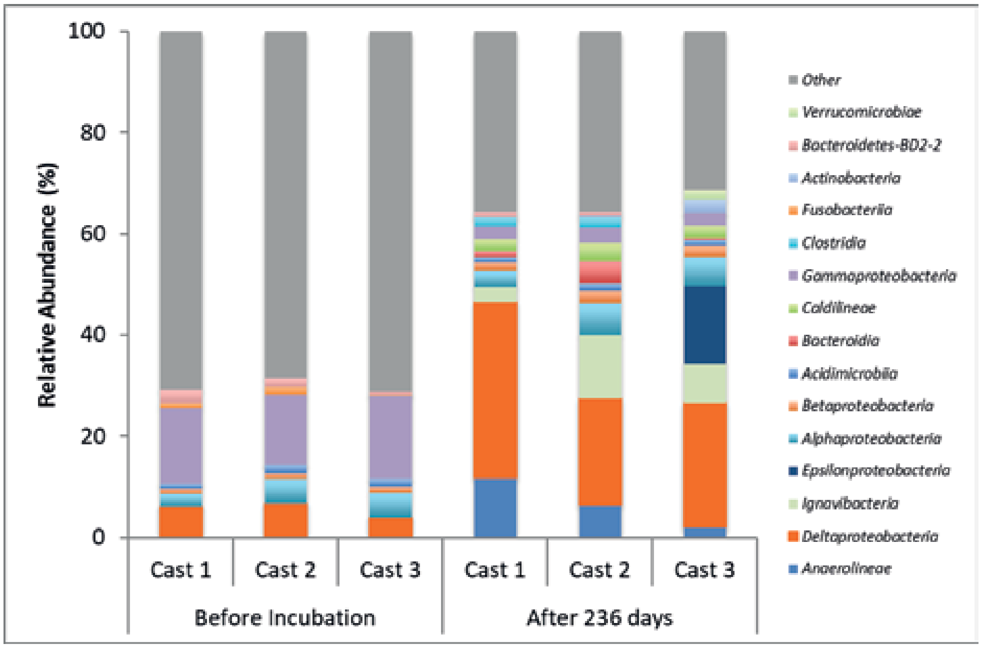

Figure 11. Changes in relative sequence abundance at the microbial Class level after 236 days in anaerobic Baffin Bay sediment 4°C incubations with 0.1% v/v diesel. OTU assignments were performed using MetaAmp and the SILVA database. The 'other' group comprises all classes that were present in less than 1% relative abundance in all samples. An enrichment of Deltaproteobacteria is evident, however a corresponding drop in sulphate concentration was not observed in these microcosms.

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 12). 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 putative hydrocarbon-degrading SRB (cf. Figure 10) 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 resolution to assess this microbial community in greater detail.

Water Column and Sediment Microbial Community Comparison

Figure 13 displays the microbial communities at the Class level through a vertical set of samples including 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 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

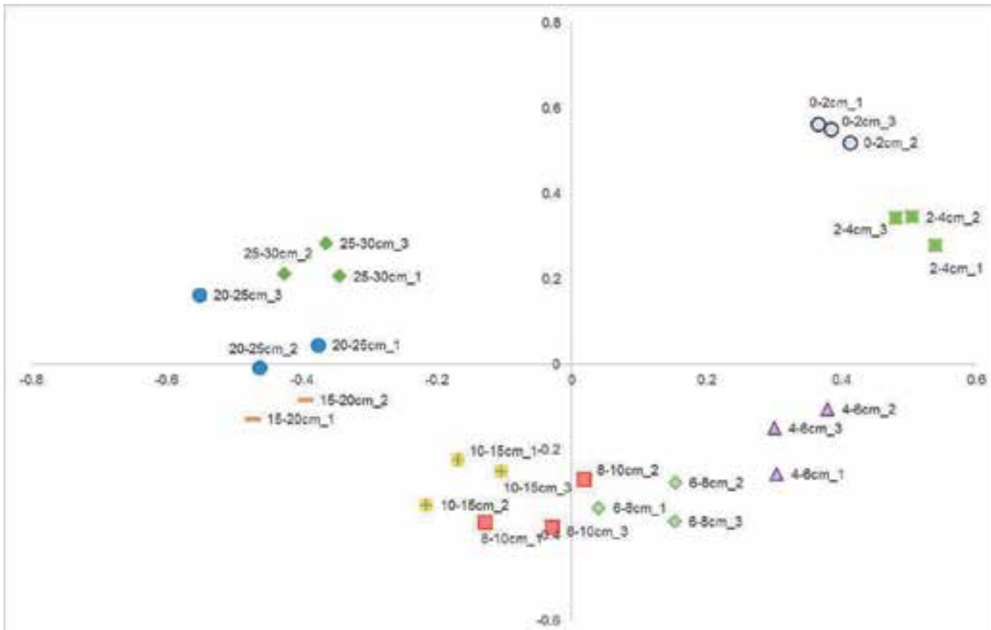

Figure 12. Non-metric multidimensional scaling of Northwest Passage sediment core 16S rRNA gene libraries (rarefied reads, Yue & Clayton Theta dissimilarity calculator; Stress: 0.120484, R-Squared: 0.960856). Three distinct separations in communities can be observed for 0-4 cm, 4-15 cm, and 15-30 cm depth intervals. Sediment oxygen penetration depth and associated total organic carbon were not measured but may explain the sudden community shifts at these depths.

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. Figures 3-5, NW Passage results) to further validate their potential as biodegradation indicators.

DISCUSSION

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 that were investigated. Sediments from Chesterfield Inlet and surrounding areas 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.

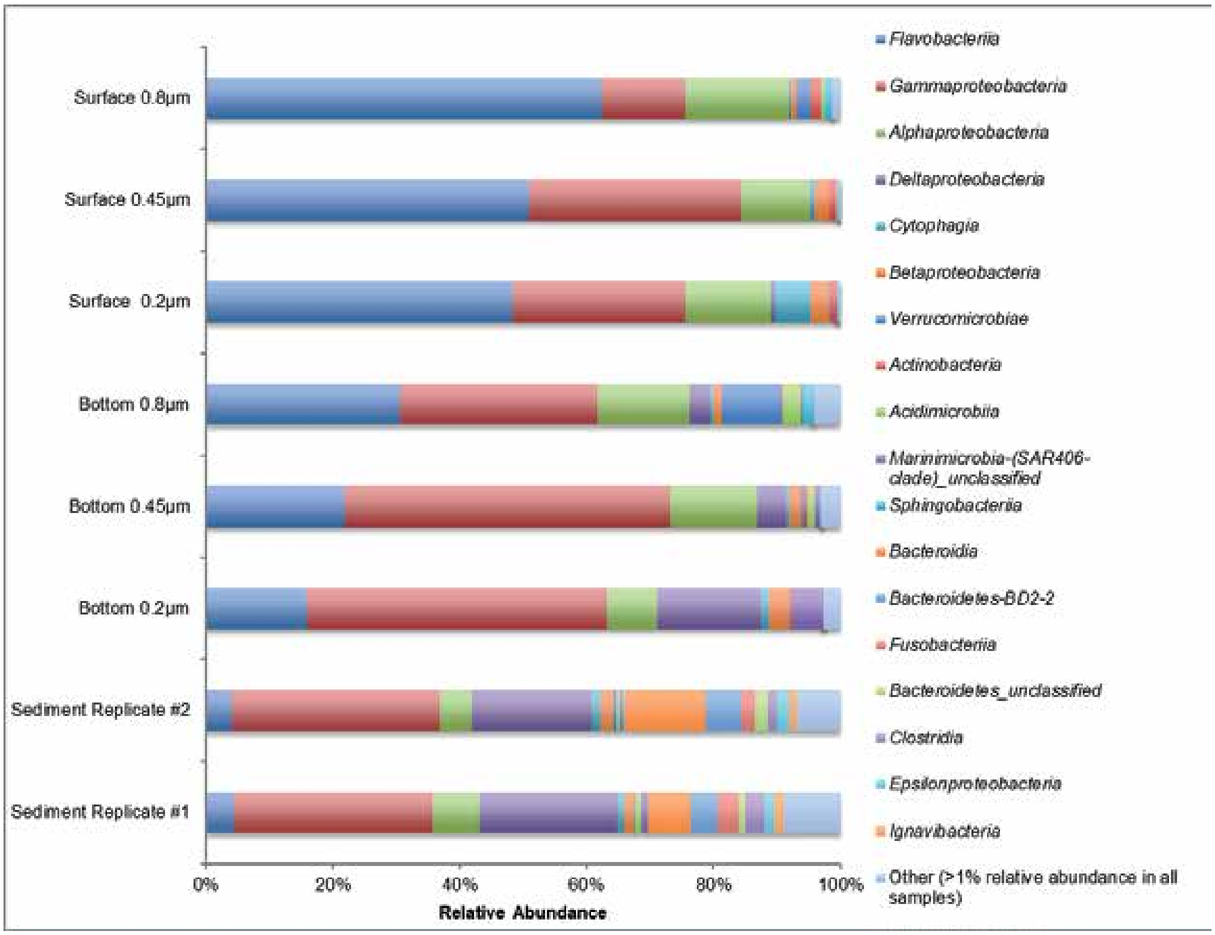

Figure 13. Differences in relative abundance of microbial classes between surface water, bottom water, and surface sediment in the Northwest Passage. 16S rRNA gene amplicon libraries were prepared from DNA extracted from filtered biomass using different filter pore sizes (0.8 µm, 0.45 µm and 0.2 µm, as indicated). OTU assignments were performed using MetaAmp and the SILVA database. The 'other' group comprises all classes that were present in less than 1% relative sequence abundance in all samples.

CONCLUSION

The funding of this ArcticNet project was crucial in years 1 and 2 (2015-16 and 2016-17) to accelerate research of microbial biodegradation of hydrocarbons in Arctic marine habitats. A strategic objective of the ArcticNet funding was to help launch a new research group in Geomicrobiology at the University of Calgary that included a focus on oil spill biodegradation in the Arctic marine environment. Thanks in large part to the momentum and network provided by the ArcticNet grant, including fieldwork opportunities onboard CCGS *Amundsen*, successful applications to the NSERC Strategic Grants (SPG) program (2015) and Genome Canada's Large Scale Applied Research Projects (LSARP) program (2016) led to a large multi-million dollar pan-Canadian research program in Arctic marine microbiology emphasizing oil spill biodegradation that is now in the process of ramping up. The investment and opportunity provided by the 'start up funding' from ArcticNet was invaluable and has been leveraged successfully so that this line of research will be able to continue.

ACKNOWLEDGEMENTS

Leah Braithwaite, Martin Fortier, Louis Fortier, Keith Levesque, Alexandre Forest, Colline Gombault, Anissa Merzouk, Vincent Auger and colleagues at the Canadian Scientific Submersible Facility in Victoria, Brent Else, Evan Edinger, Philippe Archambault, Jean-Eric Tremblay and David Barber.

REFERENCE

Kuzyk, Z.A., Gobeil, C., Goni, M., and Macdonald, R.W., 2016, Early diagenesis and trace element accumulation in North American Arctic margin sediments, Geochimica et Cosmochimica Acta, http://dx.doi.org/10.1016/j.gca.2016.12.015.

MARINE BIOGEOCHEMISTRY AND SURFACE EXCHANGE OF CLIMATE ACTIVE GASES IN A CHANGING ARCTIC SYSTEM

Project Team

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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

- Surface waters in the ArcticNet domain are largely under saturated in pCO_2 and represent a modest sink of atmospheric CO_2 during summer and fall.
- Variability in surface pCO_2 is strongly influenced by freshwater and variation in seawater temperature, with only modest contributions from primary production, excepting local short term influences associated with open water and ice-edge phytoplankton blooms.
- The timing of sea ice processes (formation, melt, and break-up) plays a controlling role in many of the factors that affect pCO_2, and therefore gase exchange, through the open water season.
- Near-surface gradients in seawater pCO_2 can result in large errors in air-sea CO_2 flux estimated from shipboard rosette and underway samples.
- In the Canadian Arctic Archipelago, photosynthesis appears to draw down both nutrients and CO_2 in the surface waters before ice melt.
- Sub-ice blooms represent an important source of DMS readily available for sea-to-air ventilation at ice breakup.
- The trace gases nitrous oxide (N_2O) and methane (CH_4) show high concentrations in the western Arctic Ocean, due to sedimentary production processes. Concentrations of CH_4 decrease to the east through biological oxidation, while elevated N_2O concentrations persist at intermediate depths of the water column.
- The ArcticNet domain is a weak source of methane to the atmosphere.
- Photoproduction of methane from dissolved organic matter is a potentially important source of methane in Canadian Arctic seas.
- The sea-surface microlayer is a source of organic aerosol precursors in the Arctic atmosphere, likely a result of photo- or oxidative-degradation of riverine organic matter which can be transported over large distances, across the entire Arctic basin.
- Material in the sea-surface microlayer that is most effective as ice nuclei, forming clouds in the atmosphere, appears to be associated with sea-ice melt.
- Intermediate and bottom waters of the Beaufort Sea are often undersaturated with respect to aragonite. The low aragonite saturation states we have observed appear to be associated with both water mass rearrangements, as well as drawdown of increasing atmospheric CO_2.
- The surface waters in the eastern Beaufort Sea (Mackenzie Shelf and Amundsen Gulf), part of the Canada Basin and the Queen Maud Gulf are already undersaturated with respect to aragonite, this may have deleterious effects on marine ecosystems, particularly organisms that secrete $CaCO_3$ skeletons/exoskeletons and shells.
- The Aragonite Compensation Depth in the Canada Basin and Beaufort Sea is shoaling as Atlantic waters, acidified by uptake of anthropogenic CO_2 in the North Atlantic, intrude at depth in the Arctic Ocean. Atlantic waters enter the Arctic Ocean through Fram Strait and Norwegian Sea/Barents Sea and reach the Canada Basin in about 20 years.
- Melt ponds are significant sources of DMS for the Arctic atmosphere.
- Ocean acidification could negatively affect DMS production during the vernal diatom bloom in the Arctic.
- Blooms developing under first-year ice (sub-ice blooms) produce large amounts of DMS. In contrast, low levels of DMS are measured under multi-year ice.
- This is a game changer! These new results indicate that large amounts of DMS are readily available for sea-to-air exchange as soon as ice breaks up and upon the formation of leads and cracks. It was previously thought that only ice algae

contributed to the water and atmospheric DMS peaks measured at ice edges.

- Based on sensitivity runs using a 1-D biogeochemical model: i) ecosystem accounts for approximately half of the ocean uptake of carbon and ii) cumulative uptake of atmospheric carbon is sensitive to uncertainties in air-ice flux during melt; (iii) depth of DIC and TA transport with brine does not have a strong effect of air-sea exchange during the subsequent open water season.
- Model simulations indicate that the decline in Arctic sea ice in recent decades was accompanied by an increase in both primary production and DMS emissions.

RESEARCH OBJECTIVES

This project's overarching objectives are:

1. To assess climate-active gas exchange in the Canadian coastal Arctic for major climate active gases, that include: (a) CO_2, (b) CH_4, (c) N_2O, and (d) DMS.
2. To assess the state of 'ocean acidification' within the ArcticNet domain.
3. To elucidate, through observation and modelling, the underlying processes controlling variability in (a) the transfer of climate-active gases, (b) the distribution of dissolved gas concentrations, and (b) the inorganic carbon system that moderates ocean acidification.

KNOWLEDGE MOBILIZATION

- Data is shared across the group and has supported numerous multi-authored publications.
- There has been synergy between government and university labs in support of government priorities. For example, the ArcticNet/Netcare program was particularly successful in bringing together scientists from different Canadian universities (UQAR, U Laval, McGill, U of Manitoba, U of Calgary, Dalhousie U, U of Toronto, U of Victoria) and the Department of Fisheries and Oceans and Department of Environment and Climate Change. The synergy between these groups of oceanographers, atmospheric scientists, and modellers allowed us to improve our understanding of the impact of oceanic gas emissions on particle formation in the Arctic atmosphere as well as improve the modeling of these sea-air interactions.
- Over the years, our group has combined efforts and overlapped with several projects, including CFL, MALINA (France), IPY-GEOTRACES, Arctic-GEOTRACES and MEOPAR, all aboard the CCGS *Amundsen*. We have also participated to a joint Canada-Germany cruise (MSM 46) in the Labrador Sea aboard the R/V *Maria S. Merian* (August 26-Sept. 24, 2015) during which we supplemented our sampling of the water column for hydrographic and carbonate parameters in Baffin Bay and along the western Labrador Sea. This cruise was conducted under the auspices of the CECAS program (Response of Coastal Ecosystems to biogeochemical and hydrographic changes in eastern Canadian Seas during the Holocene and Anthropocene).
- The group consistently demonstrates leadership in national and international assessments, initiatives and networks Samples are provided below:
    - » Team members contributed to the SWIPA report:
        - * Parmentier, F.-J.W., Christensen, T.R., Rysgaard, S., Bendtsen, J., Glud, R., Else, B., van Huissteden, J., Sachs, T., Vonk, J.E., Sejr, M.K., (2017). In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. pp 204–214. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

» Team members successfully initiated a new SCOR working group: Working Group 152: Measuring Essential Climate Variables in Sea Ice (ECV-ICE).

» We have integrated ArcticNET perspectives into SOLAS science plan: E. Brévière and the SOLAS Scientific Steering Committee (Eds.), 2016. SOLAS 2015-2025: Science Plan and Organisation. SOLAS International Project Office, Kiel, 76 pp.

» Process-based models developed by our team have been used to participate in the international 1-D and 3-D sea-ice ecosystem model inter-comparison projects of FAMOS (the Forum for Arctic Ocean Modeling and Observational Synthesis).

» A number of activities within the ArcticNet project have made a substantial contribution to BEPSII (the Biogeochemical Exchange Processes at Sea-Ice Interfaces (BEPSII), the international Scientific Committee of Ocean Research (SCOR) working group 140; see Steiner and Stefels (2017) for summary. BEPSII commentary/review publications of note:

  * N. Steiner, C. Deal, D. Lannuzel, D. Lavoie, F. Massonnet, L.A. Miller, S. Moreau, E. Popova, J. Stefels, and L. Tedesco, 2016. Elem. Sci. Anth. 4: 000084, doi: 10.12952/jounal.elementa.000084. What sea-ice biogeochemical modellers need from observers.

  * L.A. Miller, F. Fripiat, B.G.T. Else, J.S. Bowman, K.A. Brown, R.E. Collins, M. Ewert, A. Fransson, M. Gosselin, D. Lannuzel, K.M. Meiners, C. Michel, J. Nishioka, D. Nomura, S. Papadimitriou, L.M. Russell, L.L. Sørensen, D.N. Thomas, J.-L. Tison, M.A. van Leeuwe, M. Vancoppenolle, E.W. Wolff, and J. Zhou, 2015. Elem. Sci. Anth. 3: 000038, doi: 10.12952/journal.elementa.000038. Methods for biogeochemical studies of sea ice: The state of the art, caveats, and recommendations.

» Team members participated in the AMAP, 2017. Adaptation Actions for a Changing Arctic: Perspectives from the Bering-Chukchi-Beaufort Region. ArcticMonitoring and Assessment Programme (AMAP), Oslo, Norway. xiv + 255pp

- We are working with the Vancouver Aquarium to develop new data visualizations (e.g. remote sensing imagery) for their expanding Arctic gallery. These displays will enable visitors to access primary data sets in an interactive way, gaining deeper understanding of the rapid changes unfolding across this region.

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., 2017), and 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). 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).

This ArcticNet Phase III project studies the complex inter-relationship between seawater biogeochemistry and source/sink characteristics of these climate-active gases, in addition to rates and patterns of ocean acidification. Project objectives are achieved through the synthesis of past results, and using field studies to strategically fill in 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

A portion of the 2017 ArcticNet cruise of the CCGS *Amundsen* was in partnership with the NSERC Collaborative Research and Development (CRD) Network project, BaySys. The BaySys cruise planned for Hudson Bay was cancelled in 2017 because of CCG operational needs for the *Amundsen*, and has been re-scheduled for 2018. Project participants were well prepared to capitalize on the opportunity, and the resulting data set would have contributed toward the team's ArcticNet objectives in Hudson Bay, including the Hudson Bay IRIS. Team members participated on subsequent cruised section within Baffin Bay and waterways of the Canadian Arctic Archipelago. *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;
- Direct measurements of sea-air CO_2 flux using a redesigned ship-based eddy covariance 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). The saturation state of waters with respect to aragonite (Ω_{AR}) was computed using CO_2sys and the first three variables as input parameters. The $\delta^{18}O$(H_2O) was used with other hydrographic variables to determine the relative contribution of source water masses to the water column structure in the study region;
- High-frequency mapping of surface water concentrations of DMS using a sea-going automated cryogenic trap membrane inlet mass spectrometer (ACT-MIMS). Uncharted surface waters of the Northwest passage were analyzed at high-frequency for the first time in summer;
- 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;
- In collaboration with a MEOPAR-funded project, our team members conducted fieldwork in Cambridge Bay, Nunavut to validate an autonomous under-water instrument system capable of measuring $p$$CO_2$ and pH;
- Laboratory incubations were conducted to determine net production or consumption rates of methane and to assess the role of sulfur compounds (DMS, DMPS and DMSO) as precursors of methane using water samples collected from selected stations;
- Estimates of net community production from continuous ship-board measurements of biological oxygen saturation (DO_2/Ar);

Other:

- Laboratory experiments on CO_2 rejection with brines during sea-ice formation to better understand the role of forming sea ice on the carbon system of underlying seawater.

- Photoproduction of CH_4 experiments were carried out in the land-based laboratory.

RESULTS

Presentation of results is organized by research theme in the following.

Space-time distribution of dissolved CO_2 and Sea-Air CO_2 fluxes

Field studies (Else et al., 2011; Miller et al., 2011; Shadwick et al. 2011; Else et al. 2012a,b; 2013b; Forest et al. 2014; Evans et al., 2015; Burgers et al. 2017; Geilfus et al., 2018; Miller et al. submitted) have shown that:

- Surface waters in the ArcticNet domain are largely undersaturated in pCO_2 and represent a modest sink for CO_2 during the summer and fall.
- Some regions (e.g., southeastern Beaufort Sea) that have been observed to act as a weak CO_2 sink can be net-heterotrophic, and this apparent contradiction was attributed to elevated primary production prior to measurements, and through the response of the inorganic carbon system to freshwater dilution by river runoff and sea-ice melt and the presence of cold surface waters.
- Data coverage remains poor in the winter, but those data available to the team show that the partial pressure of CO_2 at the water surface of Amundsen Gulf remained undersaturated relative to atmospheric levels over much of the annual cycle.
- Enhanced air-sea CO_2 exchange relative to open water rates of exchange (i.e., 10 to 100 times higher) was observed in areas of mobile and broken sea ice in the winter season.
- Key environmental drivers include seawater temperature, sea-ice distribution and melt, other freshwater sources (e.g., rivers), local algal blooms and regional spring/fall upwelling events.
- Impact of freshwater on pCO_2 can be realized far from the freshwater source.
- Observed seasonal summer-to-autumn increase in pCO_2 of surface waters is largely attributed to the continuous uptake of atmospheric CO_2 through both summer and autumn and to the seasonal deepening of the surface mixed layer, bringing CO_2-rich waters to the surface.
- Measurement of pCO_2 using standard ship-based approaches can result in biased results in areas where freshwater is prevalent, contributing to a biased estimate of air-sea CO_2 exchange.
- Spring/fall upwelling caused high pCO_{2sw} but landfast ice prevented outgassing.
- Summer ice melt and photosynthesis caused low pCO_{2sw}, allowing strong CO_2 uptake.
- The treatment of reduced sea ice in air-sea flux calculations within the western Arctic coastal ocean could increase carbon uptake by ~ 30% over current estimates.
- Although difficult to extrapolate to the coastal seas, measurements suggest that CO_2 uptake within the southern portion of the Canada Basin will not appreciably increase with decreasing sea ice.
- A surface micro layer (SML) is widely prevalent in the ArcticNet domain and of a different composition than observed in temperate Pacific waters. The effect of the SML is an additional resistance to the air-water exchange gas, that is not explicitly accounted for by current transfer velocity parameterizations.

Inorganic Carbon System and Ocean Acidification

Field studies (Shadwick et al., 2013; Miller et al., 2014; Burt et al., 2016; Luo et al., 2016) have shown that:

- Variations in elements of the carbonate system (TA, DIC, $\delta^{13}C_{DIC}$ and Ω_{AR}) in surface waters in Hudson Bay in most cases follow the distribution of salinity.
- We are uncertain on TA concentrations received by the marine system from large rivers entering Hudson Bay, and ambiguity in salinity-TA system trends cited above in proximity to estuaries and river plumes might be attributed to high TA associated with river outflow.
- Surface waters were supersaturated with respect to aragonite in Hudson Bay (Ω_{AR} >1), but the aragonite saturation depth (Ω_{AR} = 1) shoals within 20 m of the surface in south-eastern Hudson Bay, meaning deeper waters are undersaturated and corrosive to $CaCO_3$.
- Waters in Amundsen Gulf and southeastern Beaufort Sea are more vulnerable to acidification than Antarctic waters. The Arctic waters generally experienced greater freshening, lower nutrient loading, and a lower over-all alkalinity relative to Antarctic counterparts.
- Data on the carbon system of the Beaufort Sea and southern Canada Basin dating back to the 1970s affirms the system has been a long-term sink for atmospheric CO_2, but they also show the pCO_2 in the upper halocline and deep water to be increasing, while $CaCO_3$ saturation states have decreased.
- Depth sections of Ω_{AR} reveal the presence of two distinct undersaturated layers above the Aragonite Compensation Depth (ACD) in the Canada Basin and Beaufort Sea:
    - » The upper-most undersaturated layer was fairly continuous in 2015 and extended variably from the surface to depths of 30-50 m. We attribute the aragonite-undersaturation to the input of freshwater near the surface, which effectively dilutes alkalinity, leading to lower concentrations of CO_3^{2-} and Ω_A values. Most of the photic zone, where calcifying organisms thrive, is thus already undersaturated with respect to aragonite.
    - » A second undersaturated layer, easily identifiable by its high pCO_2, spans intermediate depths of 100-200 m and consists of advected waters originating from the Pacific Ocean. These waters have accumulated metabolic and respiratory products from the North Pacific as well as their passage through the productive Chukchi Shelf and are consequently rich in CO_2 and nutrients. The presence of this layer constrains the summer supersaturation with respect to aragonite to only a thin band of water located at ~ 50-75 m, which should rapidly give way to undersaturated conditions as air-sea gas exchange and diffusion from the modified Pacific waters acidify these waters in both directions. This exacerbates the vulnerability of the region and its marine ecosystem to anthropogenic acidification. Finally, the depth of the Aragonite Compensation Depth is shoaling in the study area as Atlantic waters that make up the deeper waters are acidified by the anthropogenic CO_2 they acquired in the North Atlantic before entering the Arctic Ocean. These Atlantic waters are about 20 years old by the time they reach the Canada Basin and the Beaufort Sea.

Sea-Ice Carbon System and Flux

Field studies (Brown et al., 2015; König, 2017) have shown that:

- The dominant controls on carbon system parameters within the ice are influenced by proximity to ice/atmosphere and ice/ocean.

- pCO_2 within the ice was strongly controlled by physical processes associated with warming, while in the bottom ice, biological CO_2 uptake influences pCO_2 conditions throughout the spring/summer time series;
- The majority of the large pCO_2 reservoir retained in sea ice over winter is merely stored until spring, when freshwater dilution decreases pCO_2;
- Most of the inorganic carbon rejected from sea ice while it forms is deposited into the underlying waters; more carbon is rejected from slowly growing ice, but the carbon rejected from rapidly growing ice is injected deeper into the water column.

Aerosols and Trace Gases (DMS, CH_4 and N_2O)

Field studies (Mungall et al., 2016; 2017; Collins et al., 2017; Fenwick et al., 2017; Hussherr et al., 2017; Irish et al., 2017; Gourdal et al., 2018; Lizotte et al., in prep; Xie et al., in prep.) have shown that:

- The formation of ice in clouds is facilitated by the presence of airborne ice-nucleating particles. Ice-nucleating particles (INPs) were ubiquitous in the micro-layer and bulk seawater in Baffin Bay and the CAA.
- The sea surface micro-layer within the CAA and Baffin Bay represents a novel source of oxygenated volatile organic compounds (OVOCs) to the marine boundary layer. These compounds are an important precursor to climatically active organic aerosols.
- High-resolution measurements show high coherence between DMS distributions and several hydrographic variables (e.g. salinity). These results highlight the potential for enhancement of DMS concentrations and sea-air fluxes in hydrographic frontal zones.
- Blooms developing under ponded first-year ice (sub-ice blooms) produce large amounts of DMS (Lizotte et al., in prep.). In contrast, low levels of DMS are measured under multi-year ice.
- Global warming favours the development of melt ponds in the Arctic. Our results show that melt ponds represent a significant source of DMS for the Arctic atmosphere in spring/summer (Gourdal et al. 2018).
- Ocean acidification can decrease DMS production by up to 80% during vernal diatom blooms in the Arctic (Hussherr et al. 2017).
- An inter-annual comparison study suggests that higher fragmentation of sea ice and earlier retreat of first-year sea ice may be associated with the greater frequency of high levels of marine DMS as well as the concomitant greater frequency of atmospheric ultra-fine particle formation and growth in the CAA (Collins et al., 2017).
- Dissolved CH_4 and N_2O was observed to vary with water mass along a transect from the Bering Strait and through the CAA (Figures 1 and 2). The highest concentrations of both gases occurred in the bottom waters (PWW) of the shallow Chukchi Sea. The high N_2O concentrations on the shelf are transported through the Canada Basin until they are attenuated in the CAA. Methane concentrations were more spatially heterogeneous, reflecting a variety of localized inputs, including sources from sedimentary methanogenesis and sea-ice processes. Unlike N_2O, CH_4 was rapidly consumed through microbial oxidation in the water column, resulting in near neutral air-sea fluxes.
- The turnover time of methane in the western Baffin Bay shelf water ranged from 170 to 870 d.
- Microbial degradation of DMS, DMSP, and DMSO was unlikely a major pathway for methane production in the study area.

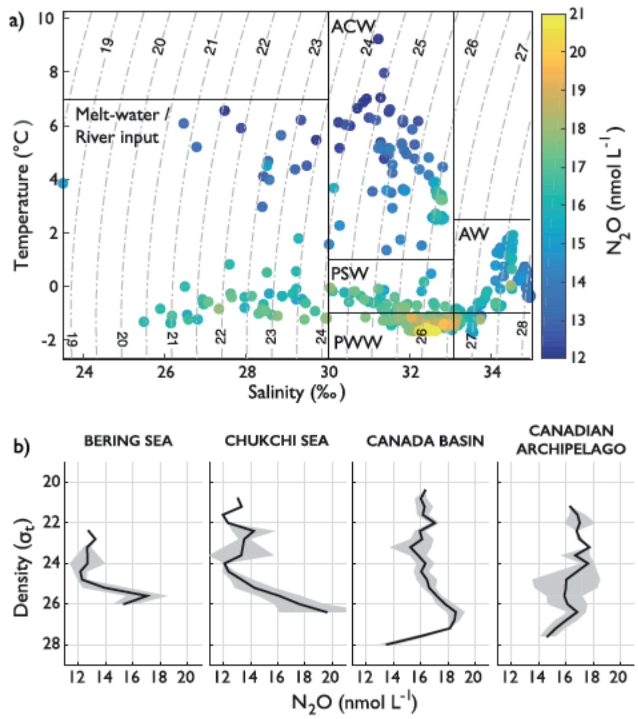

Figure 1. Salinity versus temperature plot illustrating the different water masses observed in the North American Arctic (a). Circles, squares, and triangles denote measurements from the Bering and Chukchi Seas, Canada Basin, and CAA, respectively. Density versus concentration plot averaged by sub-region (b). The grey shaded area is the standard deviation of the mean values obtained for all density surfaces in each region (Fenwick et al., 2017). © 2017, John Wiley and Sons. © 2016 American Geophysical Union. All Rights Reserved.

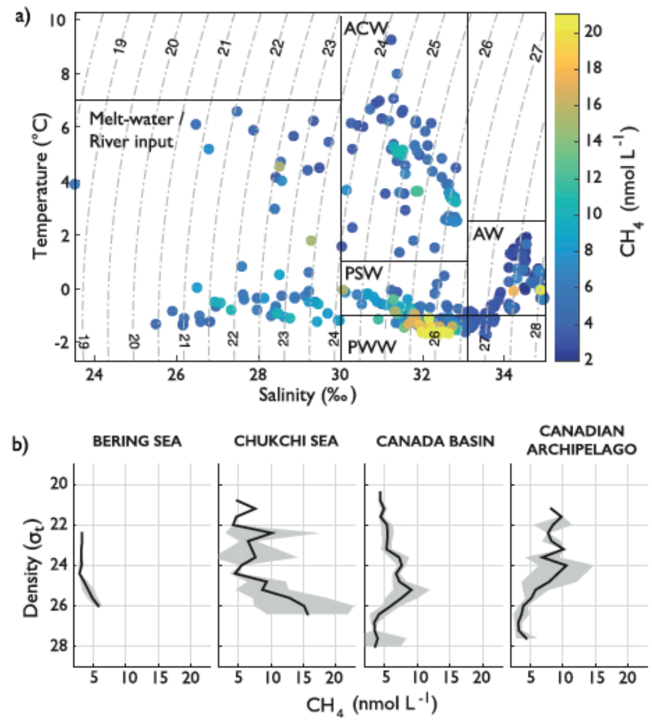

Figure 2. Salinity versus temperature plot illustrating the different water masses observed in the North American Arctic (a). Circles, squares, and triangles denote measurements from the Bering and Chukchi Seas, Canada Basin, and CAA, respectively. Density versus concentration plot averaged by sub-region (b). The grey shaded area is the standard deviation of the mean values obtained for all density surfaces in each region (Fenwick et al., 2017). © 2017, John Wiley and Sons. © 2016 American Geophysical Union. All Rights Reserved.

Biogeochemical Modeling

Modelling studies (Hayashida et al., 2017; Gali et al., 2018; Abraham et al., 2015; Hayashida et al., in prep; Mortenson et al., 2017) have shown that:

- The rich DMS data set collected during the ArcticNet cruises was used to develop a new model that reproduces Arctic DMS distribution from satellite data (Gali et al., 2018).
- Sea-ice DMS data collected in the field also served to fuel a 1-D model investigating the potential impact of bottom-ice DMS production on DMS on emissions in the Arctic during spring/summer. The model results highlight that taking into account the biogeochemistry of DMS within the sea ice itself can enhance, by up to 20%, the fluxes of oceanic DMS in marginal ice zones (Hayashida et al., 2017).
- An improved parameterization for light penetration through ice with variable snow cover at the surface has been developed, with the purpose of applying the sub-ice light field to an under-ice ecosystem (Abraham et al. 2015).
- A 3-D biogeochemical model of the coupled ice and ocean has been developed. We have implemented

a sulfur cycle and added carbon fluxes due to ice in the 3-D regional model for the Arctic Ocean, based on development, implementation, and analyses of the sulfur and carbon systems in the 1-D model of the sea water and ice. The 3-D model runs and analyses of the respective sulfur and carbon systems are being investigated, with publication of results planned later this year and the next year. Preliminary analysis of the multi-decadal (1979-2015) model simulation shows that: 1) spatial distributions of primary production and sea-surface DMS become relatively high in May-August in the Arctic domain; 2) sea-ice biogeochemistry can make a significant contribution to primary production and the oceanic DMS production can ccur in May-June in certain regions; and 3) the pan-Arctic primary production and ocean DMS emissions have increased almost linearly over the recent decades (1996-2015).

- Process-based model studies (Mortenson et al., 2017) have shown that carbon uptake during the open-water season is linked to biological productivity, high-[DIC] brine rejection during ice growth, release of low-[DIC] meltwater during ice melt, and ikaite formation in the ice. The implementation of carbon system in the model allows for investigation of the ocean pH and saturation of calcium carbonate over the period of the model's control run (1979-2015). A study of the model output is underway. Early result confirm that sea ice is a driver of carbon fluxes due to growth and melt as well as through providing a habitat for sea ice algae. The latter influence the phenology of the under-ice and subsequent open-water pelagic ecosystem.

DISCUSSION

A selection of discussion points over the years include:

- High rates of wintertime CO_2 uptake in mixed-ice and ocean cover (Else et al., 2011) enforces the long-standing position (e.g., Anderson et al., 2004) that CO_2 fluxes in Arctic polynyas needs to be higher relative to other open ocean environments to explain unusually high dissolved CO_2 concentrations at depth. The implication of this research is that an increase in open water during the winter (as expected with global warming) should promote higher wintertime uptake of CO_2, provided waters remain undersaturated in CO_2 with respect to the atmosphere. The potential for progressively more open water during the winter season in the Arctic is a distinct possibility. These findings were transformative as wintertime uptake of CO_2 by the ocean had previously not been considered.
- Sea ice has strong and varied influences on surface seawater pCO_2. For much of the cold season sea ice was observed to encourage high under-ice pCO_2 (Fransson et al., 2013; Else et al., 2013a; Shadwick et al., 2011) presumably through brine rejection and capping the product of respiration. Alternatively summer ice melt and photosynthesis caused low pCO_2, allowing strong CO_2 uptake. Our ability to predict consequences of changing sea ice on seawater pCO_2 lies in our ability to understand those sea-ice processes that underpin its variability.
- The synthesis of annual uptake of CO_2 within the polynya region (Figure 3) (Else et al., 2013a, 2012b; Shadwick et al., 2011) is based on arguably the most comprehensive CO_2 system data set of any polar sea globally. Research challenges the universality of the existing model of air-sea CO_2 exchange for High Arctic Polynyas proposed by Yager et al., (1995) from measurements made during the Northeast Water Polynya study. According to Yager et al. (1995), a strong springtime water column CO_2 uptake in the Amundsen Gulf polynya associated with primary production, is balanced by strong air-sea CO_2 exchange during the fall season. Instead, data from the Cape Bathurst Polynya show that air-sea exchange throughout the winter season offsets summertime CO_2 deficit in surface waters.

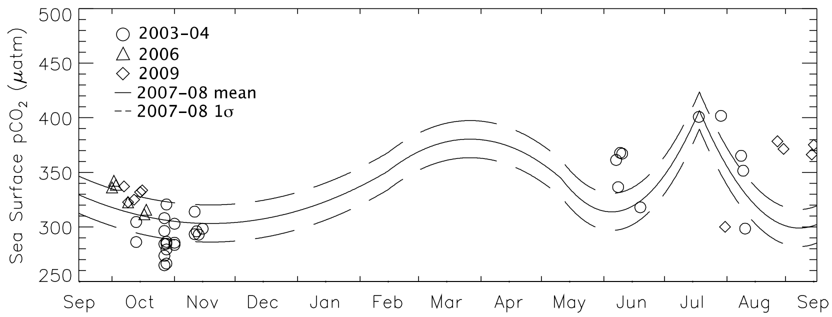

Figure 3. pCO_2sw observations made in the Cape Bathurst polynya region during the CASES cruises of the CCGS Radisson and Amundsen (2003-04, Mucci et al., 2010), ArcticNet (2006 and 2009) cruises of the CCGS Amundsen, and 2007-08 CFL/ArcticNet Amundsen expedition (Else et al., 2012). Adapted from Else et al. (2013). © 2013, John Wiley and Sons. © 2013 American Geophysical Union. All Rights Reserved.

- Further reduction in summertime sea-ice coverage would likely not significantly enhance CO_2 uptake by Arctic surface waters because of nutrient limited biological productivity attributed to strong stratification associated with pooling of sea-ice melt (Else et al. 2013b).
- Fenwick et al., (2017) determined that the cycling of CH_4 and N_2O on the Arctic continental shelves is affected by primary productivity, the resulting carbon export and transport of organic matter associated with ice melt and river run-off. It follows that if primary productivity increases in shelf seas with regional warming, as expected (Arrigo and van Dijken, 2015), we would expect increased carbon export, potentially altering the N_2O cycle. In the case of methane, enhanced emissions from sediments may increase CH_4 available to the water column, but what reaches the atmosphere depends on water depth and the rate of CH_4 oxidation (to CO_2) within the sediments and water column.
- Zhang and Xie (2015) demonstrated that methane can be photochemically produced from dissolved organic matter (DOM) in highly colored freshwater in the Saguenay River and that DMS can enhance the methane photochemical source. Xie et al. (in prep) further confirmed that photoproduction of methane also takes place in coastal and open-ocean waters. The fact that DMS can serve as a precursor of photochemically-produced methane reveals a strong linkage between the cycling of these two important trace gases. The photodegradation of dissolved organic matter is potentially a significant source of methane in open waters of the Arctic Ocean. The photochemical route provides an alternative, abiotic pathway for deciphering the oceanic methane paradox.
- The intensification of the hydrological cycle associated with global warming is leading to a freshening of the Arctic Ocean (cf. Carmack et al., 2016) exerting strong influence on the carbon system. Increased river discharge and ice melt may increase organic matter import to the surface waters of the Arctic Ocean, potentially accelerating the processes that produce CO_2, CH_4, DMS and N_2O. Freshwater (FW) in the marine system promotes stratification, restricting mixing between the surface layer and intermediate and bottom waters. Resulting stratification allows the build of pCO_2 and inorganic carbon (and drop in pH) lower in the water column. Microbial and photochemical processes convert organic material carried by rivers and melting sea ice back to carbon dioxide (CO_2), augmenting the store of inorganic carbon, including pCO_2 pool. Increased dissolved CO_2 decreases the pH of seawater (increasing acidity). FW has lower buffering capacity (especially glacier melt) relative

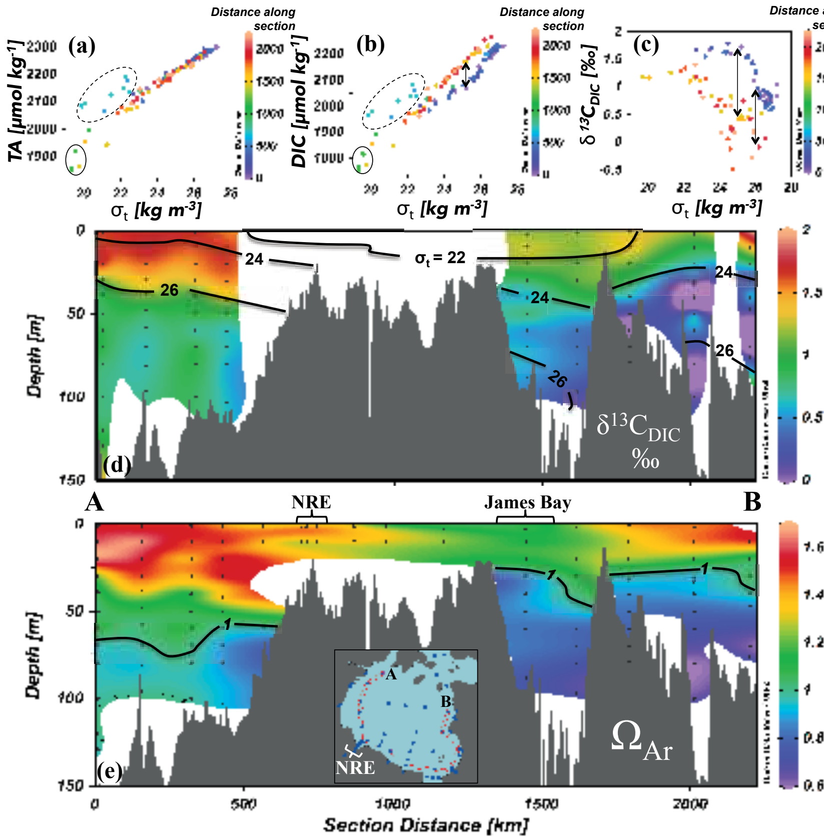

Figure 4. Variations in TA (a), DIC (b), and $\delta^{13}C_{DIC}$ (c) with in situ density anomaly (σ_t - observed density – 1000 kg m^{-3} along the northwest–northeast (A–B) coastal transect (inset map of transect is shown in lower panel). Dashed ellipses surround data within the Nelson River Estuary, while solid ellipses surround data with freshwater composition (f _SIM) ≥0.05 (located along southern coastline). Vertical arrows illustrate differences in DIC and $\delta^{13}C_{DIC}$ between waters in western Hudson Bay (blue–purple points) and eastern Hudson Bay (red–yellow points). (d) Cross section of $\delta^{13}C_{DIC}$ along the coastal transect with isopycnals of in-situ density anomaly (σ_t , kg m^{-3}). (e) Cross section of Ω_{AR} with solid line representing the aragonite saturation horizon (Ω_{AR} =1).

to seawater, and thus freshening of Arctic marine system increases susceptibility to OA (AMAP, 2013). FW is unevenly distributed in the Arctic Ocean. High surface pCO_2 has been observed to be associated with strong riverine signals across the CAA and Nares Strait (Burgers et al. 2018; Geilfus et al. 2018). On the other hand, areas influenced by sea-ice melt and glacier melt inflow are associated with low surface pCO_2 (Burgers et al., 2018). Our observations of an accumulation in DIC and drop in pH and Ω_{AR} within intermediate and deeper waters, and shoaling of the Ω_{AR} in the Southeast Beaufort and Hudson Bay (e.g., Figure 4) is in part attributed to stratification associated with freshwater (Shadwick et al., 2013; Miller et al., 2014; Burt et al., 2016; Luo et al., 2016). Fenwick et al., (2017) report that in the CAA, CH_4 was frequently super-saturated in fresh surface waters, and they observed a strong negative correlation between CH_4 and salinity (Figure 5), suggesting freshwater sources of CH_4 from ice melt and/or rivers. These works highlight the need to track and anticipate changes in the fresh water balance and sources as an important determinant of changes to both future air-sea gas exchange budgets and rates and states of ocean acidification.

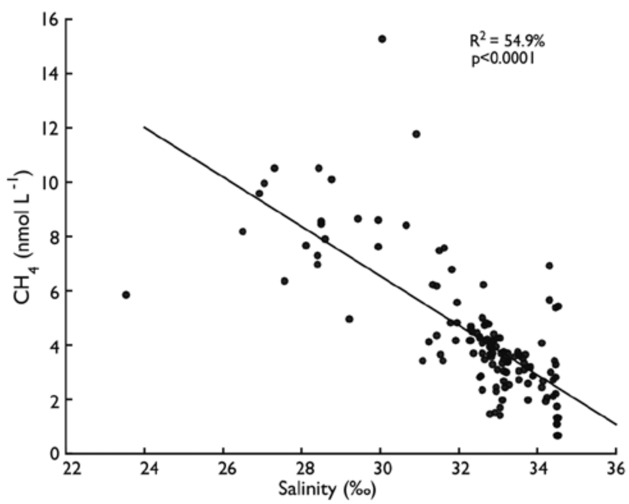

Figure 5. An inverse relationship between CH_4 and salinity in the CAA and Baffin Bay (Fenwick et al., 2017). © 2017, John Wiley and Sons. © 2016 American Geophysical Union. All Rights Reserved.

- Detection of change to the carbonate system in Canadian shelf systems is challenging. Beaupré-Laperrière et al. (in prep), reveal that, on a decadal timescale, the changes in water chemistry associated with CO_2 uptake, as reflected by changes in the DIC:TA ratio, are relatively small in amplitude relative to the large naturally-occurring seasonal and interannual variability in this highly dynamic environment (Figure 6). The inherent challenge in constraining the rate of anthropogenic acidification (ongoing) is to estimate the individual contributions of biological and physical processes affecting acidification parameters. These processes include photosynthesis, respiration, advection and diffusion, most of which are modulated by sea-ice processes that restrict air-sea gas exchange, dictate the timing of phytoplankton blooms and influence surface salinity through seasonal melting and freezing.
- Results from an intensive study indicates that the sea surface microlayer (SML) is ubiquitous in the Arctic (Wurl et al. 2011). High concentrations of transparent exopolymer particles found in SML were found under sea ice, suggesting a link to ice algal production. The microlayer is thought to affect light penetration, surface wave properties, and air-sea exchange. Additionally research bolsters our understanding on the link among, sea ice, the SML and climate relevant particles and gases in the marine boundary layer.

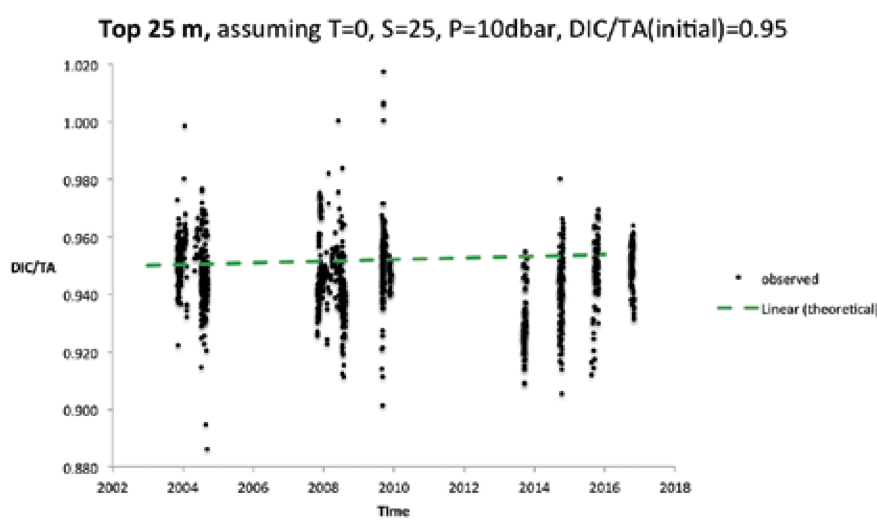

Figure 6. Theoretically-calculated increase in DIC/TA ratio over 13 years (2003-2016) assuming instant equilibration of surface waters with annual mean global atmospheric CO_2 concentrations (red line) and range of DIC/TA ratios observed in the top 25 m of the Canada Basin, Eastern Beaufort Sea and Canadian Arctic Archipelago (dots). (Beaupré-Laperrière et al. in prep.)

- The concentrations of ice nucleating particles (INPs) in the microlayer and bulk seawater of the CAA and Baffin Bay were similar to observations from other locations off the coast of North America. However, i) the average microlayer concentration was lower than previous observations made near Greenland in the Arctic, and ii) a significant INP enrichment in the microlayer, relative to bulk seawater was not observed. Analyses suggest melting sea ice to be important for INP production. As Arctic sea ice decreases, INP production in the microlayer and bulk seawater could play a larger role. Further research is needed to understand INP production in Arctic waters, their response to changing climate (Irish et al., 2017).
- The marine source of oxygenated volatile organic compounds (OVOCs) measured from the Amundsen are thought to result from dissolved organic matter in Arctic waters. As sea ice retreats and dissolved organic carbon inputs to the Arctic increase, the impact of this source on the summer Arctic atmosphere is likely to increase (Mungall et al., 2017). Changing sea ice concentration will thus likely impact the marine production of these materials, and subsequent concentration in the marine boundary layer, although predicting cause and effect requires additional study.
- Two important and previously underestimated sources of DMS for the Arctic atmosphere have been identified: under-ice blooms and melt ponds. Our results show that DMS concentrations associated with blooms developing under first-year ice (FYI) may be as high as those generally measured in marginal ice blooms (Lizotte et al. in prep.). This reservoir of DMS is readily available for release to the atmosphere when ice breaks up and upon the formation of leads and cracks. These pulses of DMS from the ocean may contribute to the DMS peaks often measured in the atmosphere close to the ice edge. In contrast, very low levels of DMS are found under multi-year ice (MYI) and consequently at their margins. The gradual replacement of MYI by FYI will thus profoundly change the dynamics of DMS in the Arctic and the spatiotemporal pattern of DMS emissions. An inter-annual comparison study suggests that higher fragmentation of sea ice as well as earlier seasonal retreat of sea ice could lead to the increased frequency of high marine DMS levels and a concomitant increase in ultra-fine particle formation and growth in the atmosphere (Collins et al., 2017). Melt ponds are increasingly important in the Arctic in spring and summer when they may cover up to 90% of the ice surface. Several melt ponds were investigated for their DMS production during the ArcticNet cruises. Our data showed that DMS levels in melt ponds may be as high as in open waters during marginal ice blooms (Gourdal et al., 2018). Colonization of the melt pounds by the ice-related biota (microalgae and bacteria) proved to be essential to initiate DMS production in the melt ponds. We further demonstrated that DMS emissions from the melt ponds could significantly contribute to atmospheric DMS in the CAA (Mungall et al. 2016).
- Ocean acidification may reduce DMS production during springtime diatom blooms in the Arctic. Results from a pH manipulation experiment showed that DMS concentrations produced during a diatom bloom in Baffin Bay may decreased by as much as 80% with decreasing pH (Hussherr et al. 2017). These results indicate that, by decreasing DMS emissions, OA could accelerate regional warming as DMS is tied to cloud formation in marine environments.

CONCLUSION

Climate change has already affected change on the Arctic Ocean, with strong potential impacts on biogeochemical cycling. Physical changes, including increased river discharge, rapid melt of glaciers, warming surface waters, reduced permanent ice cover, and permafrost thaw, have been linked to increased influence on primary productivity with

spin-off effects on the biogeochemical cycling of carbon and other nutrients in this ocean region (Macdonald et al. 2015). Our work has contributed important information on the distribution of dissolved trace gases, biogeochemical cycles that give rise to their distribution, the regional status of OA, and rates of acidification across a variety of coastal shelf environments within the ArcticNet domain, and has led to unprecedented synthesis of observations of dissolved gases, and components of the carbon system affecting OA across the N. American Arctic Ocean. Insights on the processes forcing seawater biogeochemistry have, and are furthering modeling initiatives to examine the sensitivity of biogeochemical processes that dictate air-sea exchange of climate relevant gases and ocean acidification to changing Arctic. Further climate-driven changes to the Arctic Ocean will undoubtedly occur. Our results can provide a benchmark data set against which to compare future measurements, and understanding the impacts of changes to the physical system on biogeochemical cycling will require ongoing data collection across the various domains of the Canadian maritime Arctic.

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REFERENCES

Abraham, C., Steiner, N., Monahan, A., Michel, C., (2015) Effects of subgrid-scale snow thickness variability on radiative transfer in sea ice. J. Geophys. Res.: Oceans, 120, pp. 5597-5614.

AMAP, 2013. AMAP Assessment, Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme, Oslo, Norway.

Anderson, L. G., E. Falck, E. P. Jones, S. Jutterström, and J. H. Swift (2004), Enhanced uptake of atmospheric CO_2 during freezing of seawater: A field study in Storfjorden, Svalbard, J. Geophys. Res., 109, C06004, doi:10.1029/2003JC002120.

Arrigo, K. R. and van Dijken, G. L. (2015). Continued increases in Arctic Ocean primary production. Progress in Oceanography, 136:60–70.

Azetsu-Scott, K., A. Clarke, K. Falkner, J. Hamilton, E. P. Jones, C. Lee, B. Petrie, S. Prinsenberg, M. Starr, and P. Yeats (2010), Calcium carbonate saturation states in the waters of the Canadian Arctic Archipelago and the Labrador Sea, J. Geophys. Res. Ocean., 115(11), 1–18, doi:10.1029/2009JC005917.

Azetsu-Scott, M. Starr, Z-P Mei and M. Granskog, (2014) Low calcium carbonate saturation state in an Arctic inland sea having large and varyhing fluvial inputs: the Hudson Bay system. J. Geophys. Res. Ocean, 119, 6210– 6220, doi:10.1002/2014JC009948.

Bates, N., and J. Mathis (2009), The Arctic Ocean marine carbon cycle: evaluation of air-sea CO_2 exchanges, ocean acidification impacts and potential feedbacks, Biogeosciences, 6, 2433–2459.

Brown, K.A., Miller, L.A., Mundy, C.J., Papakyriakou, T., Francois, R., Gosselin, M., Carnat, G., Swystun, K., Tortell, P.D. (2015) Inorganic carbon system dynamics in landfast Arctic sea ice during the early-melt period. Journal of Geophysical Research C: Oceans, 120 (5), pp. 3542-3566.

Burgers T M, Miller L A, Thomas H, Else B G T, Gosselin M, Papakyriakou, T. (2017). Surface water pCO_2 variations and sea-air CO_2 fluxes during summer in the eastern Canadian Arctic. Journal of Geophysical Research (Oceans). 122 (12) 9663-9678, 2017JC013250.

Burt, W.J., Thomas, H., Miller, L.A., Granskog, M.A., Papakyriakou, T.N., Pengelly, L. (2016) Inorganic carbon cycling and biogeochemical processes in an Arctic inland sea (Hudson Bay) Biogeosciences, 13 (16), pp. 4659-4671.

Chang R, Sjostedt S, Pierce J, Papakyriakou T, Scarratt M.G., Michaud S, Levasseur M, Leaitch W.R. (2011). Relating Atmospheric and Oceanic DMS Levels to Particle Nucleation Events in the Canadian Arctic. J. Geophys Res. doi.org/10.1029/2011JD015926.

Carmack, E. C. et al. (2016), Freshwater and its role in the Arctic Marine System: Sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans, J. Geophys. Res. Biogeosci., 121(3), 675–717.

Collins, D., Burkart, J., Chang, R. Y.-W., Lizotte, M., Boivin-Rioux, A., Blais, M., Mungall, E.L., Boyer, M., Irish, V.E., Massé, G., Kunkel, K., Tremblay, J.-E., Papakyriakou, T., Bertram, A.K., Bozem, H., Gosselin, M., Levasseur, M., Abbatt, J.P.D. Frequent Ultrafine Particle Formation and Growth in the Canadian Arctic Marine Environment. Atmos. Chem. Phys., 17: 13119-13138, 2017.

Evans, W., Mathis, J.T., Cross, J.N., Bates, N.R., Frey, K.E., Else, B.G.T, Papakyriakou, T.N., De Grandpre, M.D., Islam, F., Cai, W.-J., Chen, B., Yamamoto-Kawai, M., Carmack, E., Williams, W.J., and T. Takahashi. (2015). Sea-air CO_2 exchange in the western Arctic coastal ocean. Global Biogeochemical Cycles. 29: 1190-1209.

Else, B.G.T., Papakyriakou, T.N., Asplin, M.G., Barber, D.G., Galley, R.J., Miller, L.A., Mucci, A. Annual cycle of air-sea CO_2 exchange in an Arctic Polynya Region (2013a) Global Biogeochemical Cycles, 27 (2), pp. 388-398.

Else, B.G.T., Galley, R.J., Lansard, B., Barber, D.G., Brown, K., Miller, L.A., Mucci, A., Papakyriakou, T.N., Tremblay, J.-É., Rysgaard, S. Further observations of a decreasing atmospheric CO_2 uptake capacity in the Canada Basin (Arctic Ocean) due to sea ice loss (2013b) Geophysical Research Letters, 40 (6), pp. 1132-1137.

Else, B.G.T., Galley, R.J., Papakyriakou, T.N., Miller, L.A., Mucci, A., Barber, D. Sea surface p CO_2 cycles and CO_2 fluxes at landfast sea ice edges in Amundsen Gulf, Canada (2012a) Journal of Geophysical Research: Oceans, 117 (9).

Else, B.G.T., Papakyriakou, T.N., Galley, R.J., Mucci, A., Gosselin, M., Miller, L.A., Shadwick, E.H., Thomas, H. Annual cycles of pCO_2 in the southeastern Beaufort Sea: New understandings of air-sea CO_2 exchange in arctic polynya regions (2012b) Journal of Geophysical Research: Oceans, 117 (4), art. no. C00G13.

Else, B.G.T., Papakyriakou, T.N., Galley, R.J., Drennan, W.M., Miller, L.A., Thomas, H. Wintertime CO_2 fluxes in an Arctic polynya using eddy covariance: Evidence for enhanced air-sea gas transfer during ice formation (2011) Journal of Geophysical Research: Oceans, 116 (9), art. no. C00G03.

Fenwick, L. Zimmerman, S., Williams, B., Vagle, S., Capelle D.W., and P.D. Tortell. 2016. Methane and nitrous oxide distributions across the North American Arctic Ocean during summer, 2015. Journal of Geophysical Research-Oceans, Oct. 2016. doi: 10.1002/2016JC012493.

Forest, A., Coupel, P., Else, B., Nahavandian, S., Lansard, B., Raimbault, P., Papakyriakou, T., Gratton, Y., Fortier, L., Tremblay, J.-É., Babin, M. Synoptic evaluation of carbon cycling in the Beaufort Sea during summer: Contrasting river inputs, ecosystem metabolism and air-sea CO_2 fluxes (2014) Biogeosciences, 11 (10), pp. 2827-2856.

Fransson, A., Chierici, M., Miller, L.A., Carnat, G., Shadwick, E., Thomas, H., Pineault, S., Papakyriakou, T.N. Impact of sea-ice processes on the carbonate system and ocean acidification at the ice-water interface of the Amundsen Gulf, Arctic Ocean (2013) Journal of Geophysical Research: Oceans, 118 (12), pp. 7001-7023.

Galí, M., Levasseur, M., Devred, E., Simó, R., and Babin, M.: Diagnosing sea-surface dimethylsulfide (DMS) concentration from satellite data at global and regional scales, Biogeosciences Discuss., https://doi.org/10.5194/bg-2018-18, in review, 2018.

Geilfus, N.-X., M.L. Pind, B.G.T. Else, R.J. Galley, L.A. Miller, H. Thomas, M. Gosselin, S. Rysgaard, F. Wang, and T.N. Papakyriakou, (2018) Spatial and temporal variability of seawater pCO_2 within the Canadian Arctic Archipelago and Baffin Bay during the summer and autumn 2011, Continental Shelf Research, 156, 1-10, CSR_2017_155_R1, (Published 15 March, 2018), doi.org/10.1016/j.csr.2018.01.006.

Gourdal, M., Lizotte, M., Massé, G., Gosselin, M., Scarratt, M., Levasseur, M. Dimethylsulfide dynamics in first-year sea ice melt ponds in the Canadian

Arctic Archipelago. Biogeosciences Discussions, doi.org/10.5194/bg-2017-432, 2017.

Hayashida, H., Steiner, N., Monahan, A., Galindo, V., Lizotte, M., Levasseur, M. Implications of sea-ice biogeochemistry for oceanic production and emissions of dimethylsulfide in the Arctic. Biogeosciences 14: 3129-3155, 2017.

Hayashida et al. (in prep). Development of a sea-ice biogeochemical module for the Nucleus for European Modelling of the Ocean (NEMO).

Hussherr, R., Levasseur, M., Lizotte, M., et al. Impact of ocean acidification on Arctic phytoplankton blooms and dimethylsulfide production under simulated ice-free and under-ice conditions. Biogeosciences 14(9): 2407-2427, 2017.

Irish, V.E., Elizondo, P., Chen, J., Chou, C., Charette, J., Lizotte, M., et al. Ice nucleating particles in Canadian Arctic sea–surface microlayer and bulk seawater. Atmos. Chem. Phys., 17: 10583–10595, 2017.

König, D., 2017 M.Sc. Thesis, ETH Zurich, Carbon dynamics during the formation of sea ice at different growth rates.

Lansard, B., Mucci A., Miller L.A., Macdonald R.W. and Gratton Y. (2012) Seasonal variability of water mass distribution in the southeastern Beaufort Sea determined by total alkalinity and $\delta^{18}O$. J. Geophys. Res.-Oceans: 117: C03003, 19 pp., doi:10.1029/2011JC007299.

Le Quéré et al., (2017) Global carbon budget (2017) Earth Syst. Sci. Data Discuss, https://doi.org/10.5194/essd-2017-123.

Levasseur M. (2013). Impact of Arctic meltdown on the microbial cycling of sulphur. Nature Geoscience. 6:691-700.

Lizotte, M., Levasseur, M., Galindo, V., Gourdal, M., Gosselin, M., Tremblay, J.-É., Blais, M., Charrette, J. (in prep). Summer phytoplankton dynamics and DMS distribution at two constrasting Arctic ice edges: Barrow Strait and Nares Strait.

Luo Y., Boudreau B.P. and Mucci A. (2016) Disparate acidification and carbonate desaturation of deep and shallow waters of the Arctic Ocean. Nature Communications, 7: 12821, pp. 1-8 doi: 10.1038/ncomms12821.

Macdonald, R.W., Z.A. Kuzyk, and S.C. Johannessen, (2015) It is not just about the ice: a geochemical perspective on the changing Arctic Ocean. J. Environ Stud Sci., 5, 288-301.

Miller, L.A., Papakyriakou, T.N., Collins, R.E., Deming, J.W., Ehn, J.K., MacDonald, R.W., Mucci, A., Owens, O., Raudsepp, M., Sutherland, N. Carbon dynamics in sea ice: A winter flux time series (2011) Journal of Geophysical Research: Oceans, 116 (2), art. no. C02028.

Miller, L. A., F. Fripiat, B.G.T. Else, J.S. Bowman, K.A. Brown, R.E. Collins, M. Ewert, A. Fransson, M. Gosselin, D. Lannuzel, K.M. Meiners, C. Michel, J. Nishioka, D. Nomura, S. Papadimitriou, L.M. Russell, L.L. Sørensen, D.N. Thomas, J.-L. Tison, M.A. van Leeuwe, M. Vancoppenolle, E.W. Wolff, and J. Zhou, (2015). Methods for biogeochemical studies of sea ice: The state of the art, caveats, and recommendations. Elem. Sci. Anth. 3: 000038, doi: 10.12952/journal.elementa.000038.

Mortenson, E.M., Hayashida, H., Steiner, N.S., Monahan, A.M., Blais, M., Gale, M.A., Galindo, V., Gosselin, M. Hu, X., Lavoie, D., Mundy, C.J. (2017) A model-based analysis of physical and biological controls on ice algal and pelagic primary production in Resolute Passage. Elem. Sci. Anth., 5 (39).

Mucci A., Lansard B., Miller L., Papakyriakou T. (2010) CO_2 fluxes across the air-sea interface in the southeastern Beaufort Sea: the ice-free period. J. Geophys. Res -Oceans 115: C040003. doi:10.1029/2009JC005330.

Mungall, E.L., Abbatt, J.P.D., Wentzell, J.J.B., Lee, A.K.Y., Thomas, J.L., Blais, M., Gosselin, M., Miller, L.A., Papakyriakou, T., Willis, M.D., Liggio, J. Microlayer source of oxygenated volatile organic compounds in the summertime marine Arctic boundary layer (2017) Proceedings of the National Academy of Sciences of the United States of America, 114 (24), pp. 6203-6208.

Mungall, E. L., Croft, B., Lizotte, M., et al. Summertime sources of dimethyl sulfide in the Canadian Arctic Archipelago and Baffin Bay. Atmos. Chem. Phys. Discuss,15:35547-35589, 2016.

Schuster, U., et al., (2013) An assessment of the Atlantic and Arctic sea-air CO_2 fluxes: 1990-2009, Biogeosciences, 10, 607-627.

Shadwick, E.H., Thomas, H., Chierici, M., Else, B., Fransson, A., Michel, C., Miller, L.A., Mucci, A., Niemi, A., Papakyriakou, T.N., Tremblay, J.-É. Seasonal variability of the inorganic carbon system in the Amundsen Gulf region of the Southeastern Beaufort Sea (2011) Limnology and Oceanography, 56 (1), pp. 303-322.

Shakova N, Semiletov I, Salyuk A, Yusupov V, Kosmach D, Gustafsson O. (2010). Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic shelf. Science. 327(5970):1246-1250.

Steiner, N., C. Deal, D. Lannuzel, D. Lavoie, F. Massonnet, L.A. Miller, S. Moreau, E. Popova, J. Stefels, and L. Tedesco (2016) What sea-ice biogeochemical modellers need from observers, Elem. Sci. Anth.. 4: 000084, doi: 10.12952/jounal.elementa.000084.

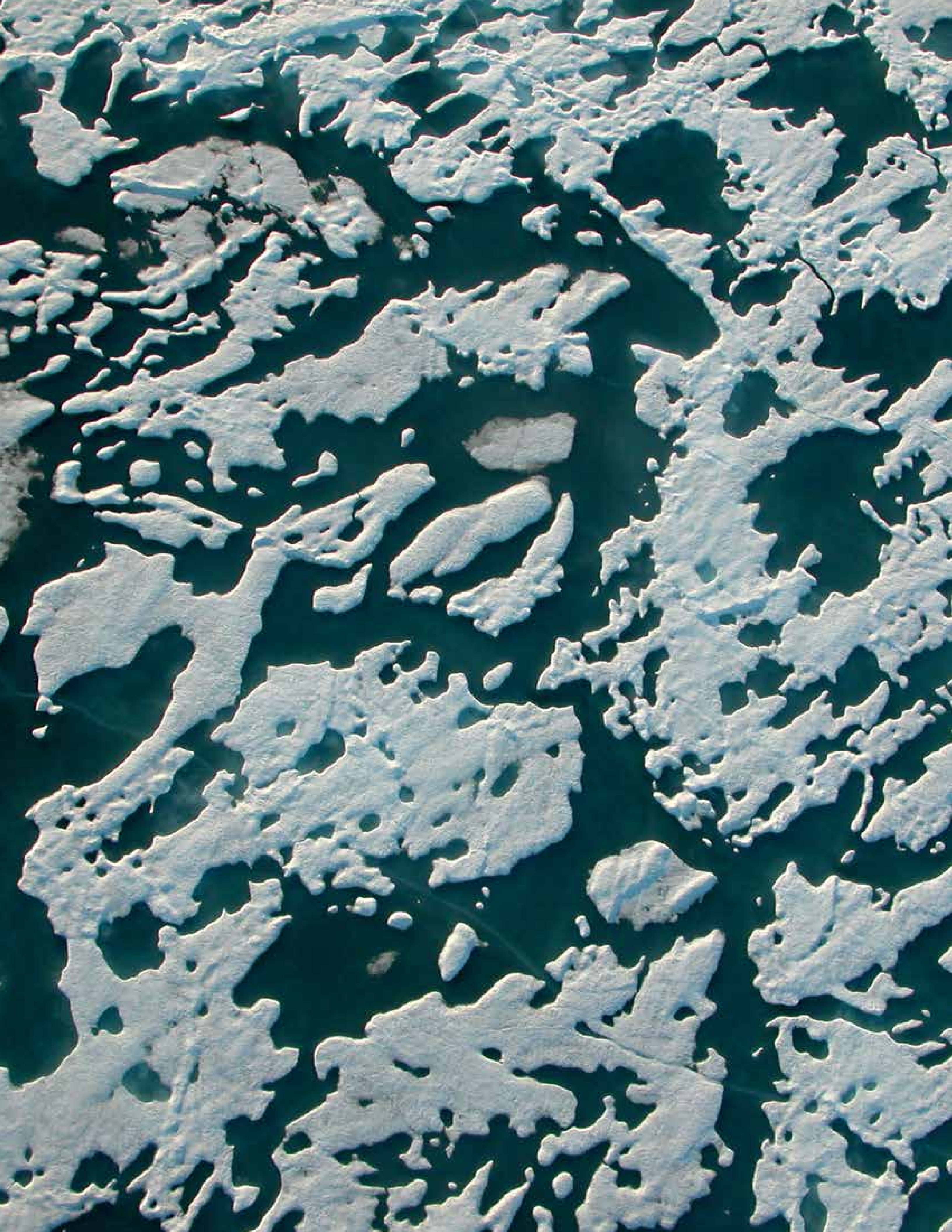
Steiner, N., Stefels, J. Commentary on the outputs and future of Biogeochemical Exchange Processes at Sea-Ice Interfaces (BEPSII). Elem. Sci. Anth., 5(0): 2325-1026, 2017.

Steiner, N.S., J.R. Christian, K.D. Six, A. Yamamoto and M. Yamamoto-Kawai (2014) Future ocean acidification in the Canada Basin and surrounding Arctic Ocean from CMIP5 earth system models, J. Geophysical Research: Oceans, 119, 1-16.

Yamamoto-Kawai, M., F. A. McLaughlin, E. C. Carmack, S. Nishino, and K. Shimada (2009), Aragonite undersaturation in the Arctic Ocean: Effects of ocean acidification and sea ice melt, Science, 326, 1098–1100.

Zhang, Y., H. Xie (2015), Photomineralization and photomethanification of dissolved organic matter in Saguenay River surface water, Biogeosciences, 12, 6823–6836.

Zhang, J., Spitz, Y. H., Steele, M., Ashjian, C., Campbell, R., Berline, L., and Matrai, P. (2010). Modeling the impact of declining sea ice on the Arctic marine planktonic ecosystem. Journal of Geophysical Research: Oceans, 115(C10):C10015.



ARCTIC GEOMICROBIOLOGY AND CLIMATE CHANGE

Project Team

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ABSTRACT

This project is motivated by the need to measure and understand the effects of sea ice and its snow cover on vertical transport between the Arctic Ocean and atmosphere. Salty liquid brine, a basic constituent of all sea ice whose chemical and physical properties vary greatly in time and space is now thought to drive processes controlling chemical contaminant pathways and greenhouse gas exchange in polar seas. For example, during winter sea ice growth, calcium carbonate may form in sea ice, releasing carbon dioxide (CO_2) that dissolves in liquid brine. Brine and its dissolved CO_2 are variably rejected from growing sea ice, potentially descending into the deep ocean sequestering CO_2 from the atmosphere. Novel results will be realized through small-scale cold lab experiments, ice tank experiments at the Sea ice Experimental Research Facility (SERF) at the University of Manitoba, and in situ field studies. Determination of the amount, timing and fate of brine rejected from sea ice at its lower and upper surfaces is paramount to making sure these globally important processes occurring at very small scales are properly accounted for in climate models used to advise the formation or change of policies.

KEY MESSAGES

- Arctic Ocean outflow and glacier-ocean interaction modify water over the Wandel Sea shelf.
- High geothermal heat flux was observed in close proximity to the Northeast Greenland Ice Stream
- Large spatial and seasonal variability in pCO_2^{SW} Canadian Arctic Archipelago and Baffin Bay are strongly controlled by sea surface temperature and sea surface salinity, which both change seasonally and/or geographically due to atmospheric temperatures, river runoff, ice melt, and ice formation.
- A new, low-cost, remote autonomous ocean-sea ice-atmosphere monitoring system is fully functional, having been tested in northwestern Hudson Bay in winter 2017.
- This project has facilitated significant and novel improvements to the CEOS Ice Mass Balance system, and consequently the Centre's ability to remotely monitor the ocean-sea ice-atmosphere interface in time and space for minimal expense.

RESEARCH OBJECTIVES

This project is motivated by the need to measure and understand the effects of glacial sources of freshwater, heat, solutes, and sea ice and its snow cover on vertical transport between the Arctic Ocean and atmosphere.

1. Baffin Bay - We retrieved moorings deployed in Baffin Bay during 2016. This project aims to understand the freshwater-marine coupling in Baffin Bay and the influence of a melting Greenland Ice Sheet on biogeochemical processes, biological production and marine ecosystem function. We finished work on surface water pCO_2 from Baffin Bay.
2. Northeast Greenland - We retrieved and redeployed oceanographic moorings from our 2016 campaign in Northeast Greenland. In addition, we collected oceanographic data in the Station Nord region. Both short-term mooring deployments in the vicinity of the glacier-ocean contact zone, and long-term mooring observation under the landfast ice are project priorities.
3. BaySys - We deployed a sea Ice Mass Balance (IMB) buoy in northwestern Hudson Bay to quantify the seasonal evolution of the thermodynamic growth and melt of snow-covered sea ice and it's motion from January to summer 2017 as part of the BaySys research project.

KNOWLEDGE MOBILIZATION

- A product, the CEOS Ice Mass Balance System, has been successfully produced and deployed in the Arctic.
- Our group participates extensively each year in Fort Whyte Alive Arctic Science Day, under the auspices of the ArcticNet Schools on Board program, introducing junior high and high school students to arctic science through an intensive, practical learning experience. We have designed the sea ice and snow lesson plan to facilitate interesting, outdoor, hands-on participation in the methods and practices of sea ice research. This program has reached over 400 students over the past six years.
- Our group participates in Science Rendezvous - an annual event at the University of Manitoba targeting young families to generate interest and create exposure to science in young children.
- This projects' investigators and members largely participate in the Arctic Science Partnership (ASP, asp-net.org), which organizes field schools for undergraduate and graduate students focusing on

the introduction of field sampling techniques, safe use of equipment and environment, and working with northern communities.

- The ASP has developed the Arctic Science Partnership Young Scientists Association to create and foster partnerships and information exchange between graduate students and post-doctoral fellows both within Canada and internationally.
- Many of this projects' NI's, as well as post-doctoral fellows, technical staff and students made presentations of their work at the Arctic Change 2017 Meeting held in Quebec City, QC from 11-15 December 2017.
- Crabeck attended the 14th International Conference on the Physics and Chemistry of Ice, 8-12 January 2018, Paul Scherer Institut, Switzerland.
- Crabeck attended the 9th International Conference on Porous Media and Annual Meeting, 8-11 May 2017, Rotterdam Nederlands.

INTRODUCTION

Weather/climate drivers affect oceanographic processes in Baffin Bay through sea ice dynamics (formation, growth, breakup, drifting pack ice and icebergs) and freshwater input from melting and calving of peripheral ice masses, such as the Greenland Ice Sheet and glaciers and ice caps of the Canadian Arctic. The Lincoln Sea - Baffin Bay - Davis Strait - Labrador Sea corridor is a central ecological hub shared between Canada and Denmark/Greenland. Massive southward flows of freshwater, sea ice and glacial ice converge along the coasts of both Canada and Greenland affecting natural and anthropogenic processes operating throughout the Baffin Bay and along its shores. The North Water Polynya (NOW), located at the northern limit of Baffin Bay, is one of the most productive marine systems in the northern hemisphere, and Inuit (and their predecessors) have occupied the region and utilized the NOW and other waters of Baffin Bay for roughly 5000 years. The climate of Baffin Bay is shaped by the Greenland Ice Sheet to the east (>1,000,000 km^2 of glacial ice) Canadian ice caps to the west (>100,000 km^2 of glacial ice), and the Arctic Ocean to the north (>10,000,000 km^2 of sea ice in winter).

Many Arctic animals, such as polar bears, seals, walruses, and seabirds, rely on marine biological productivity and on the presence of sea ice, both of which are highly dependent on climatic conditions. New and young sea ice forms are becoming a more prevalent feature in the Arctic as the icescape transitions from one dominated by multiyear ice to one of primarily first-year sea ice (Kwok, 2007, Maslanik et al., 2011, Barber et al., 2012). Reduced ice thickness and increased open water conditions in the Arctic favors phytoplankton blooms below sea ice (Rysgaard et al. 1999; Boetius et al. 2013, Mundy et al. 2009) whereas a shorter ice covered season may reduce the productivity of sea ice algae and the ice-associated ecosystem. Although much remains to be understood, recent studies provide evidence of how climate change has already resulted in clearly discernable changes in Arctic ecosystems and fisheries (Wassmann et al. 2011, Post et al., 2009).

BaySys is a 4-year $15M comprehensive study that aims to contribute to a scientific basis to understand the relative contributions of climate change and regulation on the Hudson Bay system. The role of freshwater in Hudson Bay will be investigated through field-based experimentation coupled with climatic-hydrological-oceanographic -biogeochemical modeling. BaySys is led by the University of Manitoba, Centre for Earth Observation Science (CEOS) and Manitoba Hydro. The science teams are drawn from these agencies and six Canadian academic institutions (Universities of Northern British Columbia, Québec à Rimouski, Alberta and Calgary, and Laval and Trent), in close cooperation with Manitoba Hydro, Hydro-Quebec and Ouranos. Five research teams, led by an academic and industry co-lead(s), are organized to investigate the following inter-connected subsystems: 1) Marine and Climate System, 2) Freshwater system modelling, 3) Marine Ecosystems, 4) Carbon Cycling and 5) Contaminants. The CEOS Ice Mass Balance (IMB) buoy is an autonomous Arctic marine monitoring system that provides accurate and precise meteorological and physical measurements through the ocean-sea ice-atmosphere interface. Two-way communication of data and programming instruction, instrument modularity, site-specific adaptability, and cost are our areas of focused improvement over existing solutions.

ACTIVITIES

Northeast Greenland

Mooring Recovery at Station Nord (29 Apr - 6 May 2017)

The major objective of this project was to recover (i) the ice-tethered mooring equipped with current velocity and CTD profilers, (ii) Ice Mass Balance Buoy, and (iii) a time-lapse camera, all deployed in April 2016. The recoveries were accompanied with the collecting of CTD data along the glacier terminus and within the glacier mélange.

- Fieldwork site: The landfast sea ice in the front of Flade Isblink Ice Cap terminus (Greenland)
- Participants: Igor Dmitrenko (PI), Sergei Kirillov, David Babb (CEOS), Egon Randa Frandsen (ARC)

Physical and biochemical conditions between the East Greenland Current and Fjords along east Greenland (12 Sep - 2 Oct 2017)

This project investigated physical and biogeochemical conditions above the shelf and fjords along East Greenland. The East Greenland Current transports large amounts of freshwater from the Arctic Ocean, melted sea ice, and meltwater from the Greenland Ice Cap along the Greenlandic coast. CTD-casts, measurements of microstructure turbulence and water samples were made from bottom to the surface at transects across the shelf and in the fjords along East Greenland. CTD-casts measured depth, temperature, salinity, oxygen, fluorescence and light conditions in the water column. An underway-CTD was applied in areas without sea ice and measure temperature and salinity in high spatial resolution (<10 km). Microstructure turbulence measurements contain very high resolution (centimeter scale) profiles of temperature, salinity and vertical shear and will be applied for studying vertical mixing in the water column. Water samples of nutrients, dissolved inorganic carbon, alkalinity and oxygen isotopes were collected for quantifying the oceanic CO_2-uptake, the amount and source of meltwater in the upper ocean and for analyzing water mass distributions along the shelf.

- Participants: Søren Rysgaard

BaySys (Hudson Bay System) Study - Winter Campaign

The 2017 winter estuary and mobile ice sampling program attempted to simultaneously characterize physical, biological and biogeochemical conditions in Hudson Bay sub-Arctic estuaries during peak winter sea ice cover. The aim is to improve our understanding of the winter hydrographic conditions and thermodynamic and dynamic changes in the mobile pack ice in Hudson Bay. In addition, characterizing the Nelson River plume, and its interaction with the landfast, sea ice and seawater, as it flows under and along the landfast ice cover. The focus of the winter field campaign was to retrieve marine samples from Churchill Estuary, and perform basic sampling for nutrients and biology (ice algae) from the Nelson Estuary. In addition to in-situ sampling of the ice and water column, the team installed ice-tethered moorings. These installations collected data for >30 days to capture changes in tides and weather conditions, and include under ice ADCP, CTD and optical measurements, an Ice Mass Balance buoy, Ice thickness measurements and MET stations for surface energy balance. Variables of interest also include (DOC, TN, POC, PON), $\delta^{18}O$, salinity, CTD, DIC/TA, inorganic and organic nutrients in the water and sea ice, optical properties of sea ice, rates of primary production in sea ice and surface water.

- Participants: David Babb, Nic Zilinski, Nix Geilfus, Sergei Kirillov, Igor Dmitrenko, Jens Ehn, Vlad Petrusevich

RESULTS

Baffin Bay

Data from work in Baffin Bay was published this reporting period by Geilfus et al., 2018.

Northeast Greenland

Mooring Recovery at Station Nord (29 Apr - 6 May 2017)

Current measurements along with the time series of vertical CTD profiles provide a new piece of information about the release of freshwater from beneath the glacier over the course of the year. The camera suggests providing the visual information of possible calving events that may be related to fresh water releases observed below.

Physical and biochemical conditions between the East Greenland Current and Fjords along east Greenland (12 Sep - 2 Oct 2017)

Data from work in northeast Greenland has now been published by Kirillov et al., 2017, Dmitrenko et al., 2018, and Rysgaard et al. 2018. Additional interpretation and processing will likely lead to further publications.

DISCUSSION

Geilfus et al., 2018 provide direct observations that demonstrate how freshwater from sea ice melt and riverine input affect pCO_2^{sw} differently in both the Canadian Arctic Archipelago (CAA) and Baffin Bay. pCO_2 undersaturation with respect to the atmosphere in both regions indicate that the CAA and Baffin Bay are net sink areas for atmospheric CO_2 in summer and autumn.

Kirillov et al., 2017 note that the general contribution of their study is that wind-driven water circulation and tidal flow affect the Wandel Sea shelf even during winter in the presence of a landfast sea ice cover. This subsequently imparts shelf-glacier interaction processes and cold subglacial water release. The authors question the residence time of subglacial water under the Flade Isblink Ice Cap tongue, noting that further observations are required to address this.

Dmitrenko et al., 2018 summarize their analysis, suggesting the existence of a coastal branch of the East Greenland Current southerly advecting Pacific Water of Arctic origin. They note this is consistent with earlier propositions by other including Rudels et al., 2004.

Rysgaard et al., 2018 provides the first direct evidence of geothermal heat flux from the earth's interior beneath the Greenland Ice Sheet in a deep fjord in Northeast Greenland. Heat fluxes recorded in this region account for discrepancies between observed and modeled ice flow and consequently ice mass loss. This previously unobserved heat flux could be responsible for high glacial speed areas like the Northeast Greenland ice stream.

CONCLUSION

A great deal of further work in Northeast Greenland near Station Nord has been recommended by both Kirillov et al., 2017, and Dmitrenko et al., 2018. This significance of this work lies in the novelty of both the region as remote as it is, and in the new CTD dataset collected there.

The work within the auspices of this ArcticNet project that will have positive impact on stakeholders, and significance to a myriad of scientific programs, government monitoring applications, and to northern communities is the continued development of the CEOS Ice Mass Balance buoy. As a result of ArcticNet funds, in addition to other sources of funding, it has created substantial student opportunities in a variety of fields (Environment, Geography, Geophysics, Electrical Engineering) and will dramatically advance the state-of-the-art and lower the cost of remote, autonomous monitoring stations in the Arctic marine cryosphere.

REFERENCES

Barber, D. G., Hop, H., Mundy, C. J., Else, B., Dmitrenko, I., Tremblay, J.-E., Ehn, J. K., Assmy, P., Daase, M., Candlish, L., Rysgaard, S., (2015), Selected physical, biological and biogeochemical implications of a rapidly changing Arctic Marginal Ice Zone. Progress in Oceanography. 139:122-150.

Boetius, A., Albrecht, S., Bakker, K., et al., (2013), Export of algal biomass from melting Arctic sea ice. Science 339(6126): 1430-1432. doi: 10.1126/science.1231346.

Dmitrenko, I.A. S. A. Kirillov, B. Rudels, D. G. Babb, L. T. Pedersen, S. Rysgaard, Y. Kristoffersen, and D. G. Barber, (2018), Arctic Ocean outflow and glacier-ocean interaction modify water over the Wandel Sea shelf, northeast Greenland, Ocean, Sci. Discuss., doi: 10.5194/os-2017-28.

Geilfus, N.-X., M. L. Pind, B. G. T. Else, R. J. Galley, L. A. Miller, H. Thomas, M. Gosselin, S. Rysgaard, F. Wang, and T. N. Papakyriakou, (2018), Spatial and temporal variability of seawater pCO_2 within the Canadian Arctic Archipelago and Baffin Bay during the summer and autumn of 2011, Continental Shelf Research, 156, doi: 10.1016/j.csr.2018.01.006.

Kirillov, S., Dmitrenko, I., Rysgaard, S., Babb, D., Toudal Pedersen, L., Ehn, J., Bendtsen, J., and Barber, D. (2017), Storm-induced water dynamics and thermohaline structure at the tidewater Flade Isblink Glacier outlet to the Wandel Sea (NE Greenland), Ocean Sci., 13(6), 947-959, https://doi.org/10.5194/os-13-947-2017, 2017. Published 22 Nov. 2017.

Kwok, R. (2007), Near zero replenishment of the Arctic multiyear sea ice cover at the end of 2005. Geophysical Research Letters 34, doi: 10.1029/2006GL028737.

Maslanik, J., Stroeve, J., Fowler, C., et al., 2011. Distribution and trends in Arctic sea ice age through spring 2011. doi: 10.1029/2011GL047735.

Mundy, C. J., et al. (2009), Contribution of under-ice primary production to an ice-edge upwelling phytoplankton bloom in the Canadian Beaufort Sea, Geophys. Res. Lett., 36, L17601, doi:10.1029/2009GL038837.

Post E, Forchhammer MC, Bret-Harte S, Callaghan TV, Christensen TR, Elberling B, Fox T, Gilg O, Hik DS, Ims RA, Jeppesen E, Klein DR, Madsen J, McGuire AD, Rysgaard S, Schindler D, Stirling I, Tamstorf M, Tyler NJC, van der Wal R, Welker J, and Wookey PJ (2009), Ecological dynamics across the Arctic associated with recent climate change. Science 325:1355-1358.

Rudels, B., E. P. Jones, U. Schauer and P. Erikssondels (2004), Atlantic sources of the Arctic Ocean surface and halocline waters, Polar Res., 23(2), 181–208.

Rysgaard S, Nielsen TG, Hansen B., (1999), Seasonal variation in nutrients, pelagic primary production and grazing in a high-Arctic coastal marine ecosystem, Young Sound, Northeast Greenland. Marine Ecology Progress Series 179:13-25.

Rysgaard, S., Bendtsen, J., Mortensen, J., Sejr, M.K. (2018), High geothermal heat flux in close proximity to the Northeast Greenland Ice Stream. Scientific Reports, 8:1344, doi:10.1038/s41598 -018-19244-x.

Wassmann, P., Duarte, C. M., Agusti, S. and Sejr, M. K. (2011), Footprints of climate change in the Arctic marine ecosystem. Global Change Biology, 17: 1235–1249. doi:10.1111/j.1365-2486.2010.02311.x.

PUBLICATIONS

Assmy, P., Fernández-Méndez, M., Duarte, P., Meyer, A., Randelhoff, A., Mundy, C. J., Olsen, L.A., Kauko, H.M., Bailey, A., Chierici, M., Cohen, L., Doulgeris, A.P., Ehn, J.K., … Granskog, M. A. (2017) "Leads in Arctic pack ice enable early phytoplankton blooms below snow-covered sea ice". Scientific Reports, 2017 Jan 19;7:40850. doi: 10.1038/srep40850.

Bendtsen, J., Mortensen, J., Lendert, K., Ehn, J., Boone, W., Galindo, V., Dmitrenko, I.A., Kirillov, S.A., Kjeldsen, K.K., Kristoffersen, Y., Barber, D., Rysgaard, S. (2017) "Sea ice breakup and marine melt of a retracting tidewater outlet glacier in northeast Greenland (81°N)". Scientific Reports, 7: 4941.

Boone W, Rysgaard S, Kirillov S, Dmitrenko I, Bendtsen J, Mortensen J, Meire L, Petrusevic V, Barber DG (2017) "Circulation and fjord-shelf exchange during the ice covered period in Young Sound-Tyrolerfjord, NE-Greenland (74°N)". Estuarine, Coastal and Shelf Science 194:205-216. http://dx.doi.org/10.1016/j.ecss.2017.06.021.

Burgers, T. M., Miller, L. A., Thomas, H., Else, B. G. T., Gosselin, M., & Papakyriakou, T. (2017). "Surface water pCO_2 variations and sea-air CO_2 fluxes during summer in the Eastern Canadian Arctic". Journal of Geophysical Research: Oceans, 122. https://doi.org/10.1002/2017JC013250.

Burkart, J., Hodshire, A., Mungall, E., Pierce, J., Collins, D., Ladino, L., Lee, A., Irish, V., Wentzell, J., Liggio, J., Papakyriakou, T., Murphy, J., and Abbatt, J., (2017) "Organic Condensation and particle growth to CCN sizes in the summertime marine Arctic is driven by materials more semivolatile than at continental sites", G. Res. Lett., Published online 21 OCT 2017, doi/10.1002/2017GL075671.

Campbell, K., Mundy, C.J., Belzile, C., Delaforge, A., Rysgaard, S. (2017) "Seasonal dynamics of algal and bacterial communities in Arctic sea ice under variable snow cover". Polar Biology, Online July 2017, 10.1007/s00300-017-2168-2.

Campbell, K., Mundy, C.J., Gosselin, M., Landy, J., Delaforge, A., Rysgaard, S. (2017b) "Net community production in the bottom of Arctic sea ice over the spring bloom". Geophysical Research Letters, Online August, 2017, doi:10.1002/2017GL074602.

Carlson, D.F., Boone, W., Meire, L., Abermann, J., and Soren Rysgaard (2017) "Bergy Bit and Melt Water Trajectories in Godhabsfjord (SW Greenland) Observed by the Expendable Ice Tracker". Front. Mar. Sci., 28 August 2017. https://doi.org/10.3389/fmars.2017.00276.

Christensen TR, Rysgaard S, Bendtsen J, Glud RN, Else B, van Huissteden K, Sachs T, Parmentier F-J W, Vonk JE (2017) "Arctic carbon cycling". Snow, Water, Ice, and Permafrost in the Arctic (SWIPA) Climate change and the cryosphere, 197-213.

Collins, D.B., Burkart, J., Chang, R. Y.-W., Lizotte, M., Boivin-Rioux, A., Blais, M., Mungall, E.L., Boyer, M., Irish, V.E., Masse, G., Kunkel, D., Tremblay, J.-E., Papakyriakou, T.N., Bertram, A.K., Bozem, H., Gosselin, M., Levasseur, M., Abbatt, J.P.D. (2017) "Frequent ultrafine particle formation and growth in Canadian Arctic marine and coastal environments", Atmospheric Chemistry and Physics, 17, 13119-13138, doi: 10.5194/acp-17-13119-2017.

Delaforge, A., Suárez-Morales, E., Walkusz, W., Campbell, K., Mundy, C.J. (2017) "A new species of Monstrillopsis (Crustacea, Copepoda, Monstrilloida) from the lower Northwest Passage of the Canadian Arctic". ZooKeys, 709: 1–16.https://doi.org/10.3897/zookeys.709.20181.

Dmitrenko, I.A., Kirillov, S.A., Rudels, B., Babb, D.G., Pedersen, L.T., Rysgaard, S., Kristoffersen, Y., and Barber, D.G. (2017) "Arctic Ocean outflow and glacier-ocean interactions modify water over the Wandel Sea shelf (northeastern Greenland)", Ocean Science, 13, 1045-1060, 10.5194/os-13-1045-2017.

Firoozy, N., Neusitzer, T., Desmond, D., Tiede, T., Lemes, M., Landy, J., Stern, G., Mojabi, P., Rysgaard, S., Barber, D.G. (2017) "An electromagnetic detection case study on crude oil injections in a young sea ice environment", IEEE Transactions on Geoscience and Remote Sensing, 55(8): 4465-4475, doi: 10.1109/TGRS.2017.2692734.

Gaillard, B., Meziane, T., Tremblay, R., Archambault, P., Blicher, M.E., Chauvaud, L., Rysgaard, S., Olivier, F. (2017) "Food resources of the bivalve Astarte elliptica in a sub-arctic fjord: a multi-biomarkers approach". Marine Ecology Progress Series. 567:139-156. doi:10.3354/meps12036.

Galindo V, Gosselin M, Mundy CJ, Else B, Lavaud J, Claustre H, Ehn J, Rysgaard S (2017) "Pigment composition and photoprotection of Arctic sea ice algae during spring". Marine Ecology Progress Series, 585:49-69. https://doi.org/10.3354/meps12398.

Geilfus, N.-X., M. L. Pind, B. G. T. Else, R. J. Galley, L. A. Miller, H. Thomas, M. Gosselin, S. Rysgaard, F. Wang, T. N. Papakyrakou, (2018), Spatial and temporal variability of seawater $p\mathrm{CO}_2$ within the Canadian Arctic Archipelago and Baffin Bay during the summer and autumn of 2011, Continental Shelf Research, doi.org/10.1016/j.csr.2018.01.006.

Hu, T.-B., Wang, F., Boone, W., Barber, D., Rysgaard, S. (2017) "Assessment and improvement of sea ice processing for dissolved inorganic carbon analysis". Limnology and Oceanography Methods. doi: 10.1002/lom3.10229.

Kirillov, S., Dmitrenko, I., Rysgaard, S., Babb, D., Toudal Pedersen, L., Ehn, J., Bendtsen, J., and Barber, D. (2017) "Storm-induced water dynamics and thermohaline structure at the tidewater Flade Isblink Glacier outlet to the Wandel Sea (NE Greenland)", Ocean Sci., 13(6), 947-959, https://doi.org/10.5194/os-13-947-2017, 2017. Published 22 Nov. 2017.

Meire, L., Mortensen, J., Meire, P., Juul-Pedersen, T., Sejr, M.K., Rysgaard, S., Nygaard, R., Huybrechts, P., Meysman, F.J.R. (2017) "Marine-terminating glaciers sustain high productivity in Greenland fjords". Global Change Biology, 1-14. DOI: 10.1111/gcb.13801.

Moore K, Fayek M, Lemes M, Rysgaard S, Holländer HM (2017)"Fractionation of hydrogen and oxygen in artificial sea-ice with corrections for salinity for determining meteorological water content in bulk ice samples", Cold Regions Science and Technology. 142:93-99. DOI: 10.1016/j.coldregions.2017.07.011.

Morlighem M, Williams C, Rignot E, An L, Bamber JL, Catania G, Chauche N, Dowdeswell JA, Dorsche B, Fenty I, Howat I, Hubbard A, M. Jakobsson M, Jordan TM, Kjeldsen KK, Millan R, Mouginot J, Noe BPY, Cofaigh CO, Palmer S, Rysgaard S, Seroussi H, Siegert MJ, Slabon P, Straneo F, van den Broeke MP, Weinrebe W, Wood M and Zinglersen KB (2017) "BedMachine v3: Complete bed topography and ocean bathymetry mapping of Greenland from multi-beam echo sounding combined with mass conservation". Geophysical Research Letters, 44, https://doi.org/10.1002/2017GL074954. Published 1 Nov. 2017.

Mortenson, E., Hakase, H., Steiner, N., Monahan, A., Blais, M., Gale, M.A., Galindo, V., Gosselin, M., Hu, X., Lavoie, D., Mundy, C.J. (2017) "A model-based analysis of physical and biological controls on ice algal and pelagic primary production in Resolute Passage". Elementa: Science of the Anthropocene. doi: https://doi.org/10.1525/elementa.229.

Motyka, R.J., Cassotto, R., Truffer, M., Kjeldsen, K.K., van As, D., Korsgaard, N.J., Fahnestock, M., Howat, I., Langen, P.L., Mortensen, J., Lennert, K., Rysgaard, S. (2017) "Asynchronous behavior of outlet glaciers feeding Godthåbsfjord (Nuup Kangerlua) and the triggering of Narsap Sermia's retreat in SW Greenland", Journal of Glaciology, 1-20, doi: 10.1017/jog.2016.138.

Mungall, E.L., Abbatt, J.P.D., Wentzell, J.J.B., Lee, A.K.Y., Thomas, J.L., Blais, M., Gosselin, M., Miller, L.A., Papakyriakou, T., Willis, M.D., Liggio, J. (2017) "Microlayer source of oxygenated volatile organic compounds in the summertime marine Arctic boundary layer", Proceedings of the National Academy of Sciences of the United States of America, 114 (24), pp. 6203-6208.

Neusitzer, T.D., Firoozy, N., Tiede, T.M., Desmond, D.S., Lemes, M.J.L., Stern, G.A., Rysgaard, S., Mojabi, P., Barber, D.G. (2017) “Examining the impact of a crude oil spill on the permittivity profile and normalized radar cross-section of young sea ice”. IEEE Transactions on Geoscience and Remote Sensing. TGRS-2017-00492. DOI: 10.1109/TGRS.2017.2756843.

Parmentier, F.-J.W., Christensen, T.R., Rysgaard, S., Bendtsen, J., Glud, R.N., Else, B.G.T., van Huissteden, J., Sachs, T., Vonk, J.E., and M.J. Sejr (2017) “A synthesis of the arctic terrestrial and marine carbon cycles under pressure from a dwindling cryosphere”, Ambio 46 (Suppl 1): 53. doi:10.1007/s13280-016-0872-8.

Pogorzelec, N.M., Mundy, C.J., Findlay, C.R., Campbell, K., Diaz, A., Ehn, J.K., Rysgaard, S., Gough, K.M. (2017), FTIR imaging analysis of cell content in sea-ice diatom taxa during a spring bloom in the lower Northwest Passage of the Canadian Arctic, Marine Ecology Progress Series, 569: 77-88, https://doi.org/10.3354/meps12088.

Pućko, M., Stern, G.A., Burt, A., Jantunen, L.M., Bidleman, T.F., Macdonald, R.W., Barber, D.G., Geilfus, N.-X., Rysgaard, S. (2017) “Current Use Pesticide (CUP) and legacy Organochlorine Pesticide dynamics at the Ocean-Sea-ice-Atmosphere interface in Resolute Passage, Canadian Arctic, during winter-summer transition”. Science of the Total Environment, 580:1460-1469, doi: 10.1016/j.scitotenv.2016.12.122.

Ribeiro, S., Sejr, M.K., Limoges, A., Heikkila, J., Andersen, T.J., Tallberg, P., Weckstrom, K., Husum, K., Forwick, M., Dalsgaard, T., Masse, G., Seidenkrantz, M-S., and S. Rysgaard (2017) “Sea ice and primary production proxies in surface sediments from a High Arctic Greenland fjord: Spatial distribution and implications for palaeoenvironmental studies”, Ambio, 46(Suppl 1): 106. doi:10.1007/s13280-016-0894-2.

Rysgaard, S., Bendtsen, J., Mortensen, J., Sejr, M.K. (2018), High geothermal heat flux in close proximity to the Northeast Greenland Ice Stream. Scientific Reports, 8:1344, DOI:10.1038/s41598 -018-19244-x.

Sejr, M.K., Stedmon, C.A., Bendtsen, J., Abermann, J., Pedersen, T.J., Mortsensen, J., Rysgaard, S. (2017) “Evidence of local and regional freshening of East Greenland coastal waters”. Scientific Reports, 13183, doi:10.1038/s.

Sørensen, H.L., Thamdrup, B., Jeppesen, E., Rysgaard, S., Glud, R.N. (2017) “Nutrient availability limits biological production in Arctic sea ice melt ponds”. Polar Biology. 40:1593-1606, doi: 10.1007/s00300-017-2082-7.

UNDERSTANDING THE EFFECTS OF CLIMATE CHANGE AND INDUSTRIAL DEVELOPMENT ON CONTAMINANT PROCESSES AND EXPOSURE IN THE CANADIAN ARCTIC MARINE ECOSYSTEM: HOW CAN WE PREPARE?

Project Team

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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 and mercury distribution and transport across the ocean-sea ice atmosphere interface. 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 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

Hydrocarbons in Western Hudson Bay Sediments (Whilemina Armah, Zou Zou Kuzyk, Gary Stern)

- Sediment cores at Chesterfield Inlet and Wager Bay contain hydrocarbon sources that are locally transported or are reflecting background *in situ* concentrations.

Hydrocarbons in Baffin Bay Sediment and Sea Stars (Ashley Gaden, Jake Ritchie, Alexis Burt, Gary Stern, Zou Zou Kuyzk, Robie Macdonald)

- There are regional-level differences in hydrocarbon signatures among Baffin Bay surface sediments. These contrasts are not reflected in benthic invertebrates.

Interactions between oil and sea ice (Diana Chirkova, Durell Desmond, Monika Pucko, Jake Ritchie, Feiyue Wang, Gary Stern, David Barber)

- Crude oil is able to move upward and downward in sea ice.
- Crude oil partitions in sea ice showing a trend in which low molecular weight compounds tend to move upward and heavier compounds downward and this effect increases over time.
- The presence of crude oil in the air-water interface during sea ice consolidation leads to the formation of pancake ice with non-homogeneous surface and liquid lenses of crude oil in the top section of the ice.
- The presence of crude oil in the ice increases sea ice temperature due to the oil's high thermal resistivity; that is, a consequent reduction of sea ice albedo facilitates a temperature increase of the surrounding area.
- The presence of crude oil in the ice reduces the salinity of the ice by means of brine ejection or brine drainage.
- Resultant changes in the temperature and salinity of the ice allows for a notable change in the complex permittivity of sea ice, detectable by remote sensing technologies.
- Losses of volatile crude oil components leads to a decrease in the oil's complex permittivity which further decreases the complex permittivity of the sea ice.
- In most cases, temperature was the most sensitive variable in the permittivity models, although this was sometimes frequency and oil volume fraction (Neusitzer et al. 2018).
- A national multi-sectoral OSICA Consortium has been created to prioritize and communicate research and development activities to improve policy and practices dealing with oil spills in ice-covered Arctic waters.

Biogeochemical Cycling of Mercury in the Arctic Ocean and Hudson Bay (Kathleen Munson, James Singer, Kang Wang, Debbie Armstrong, Feiyue Wang)

- The sub-surface enrichment of methylmercury (MeHg) is ubiquitous throughout the Canadian Arctic Ocean. This may have major implications for mercury bioaccumulation in Arctic marine ecosystems. The mechanism of the sub-surface production of methylmercury remains to be elucidated.
- Large differences in total mercury (THg) profiles are observed from sediment cores taken from lakes in the Nelson River Watershed.
- Compilation of atmospheric elemental mercury (Hg0) concentrations measured throughout the ArcticNet cruises generates the spatial distribution pattern of Hg0 in coastal waters of circum-North America (from tropical to Arctic regions, 6.7 °N to 77.3 °N), as well as the seasonal distribution pattern in the Amundsen Gulf region of the Arctic. The data are being compared with the results from the global chemical transport model.

Mercury and stable isotopes in decapods species, Beaufort Sea (Ainsleigh Loria, Alexis Burt, Gary Stern)

- Average total mercury, $\delta^{15}N$ and the proportion of monomethyl mercury increased from smaller decapods species (*Eualus gaimardii*) to larger species (*Sclerocrangon boreas* and *Sclercangon ferox*).
- There were significant differences in levels of total mercury, monomethyl mercury, $\delta^{15}N$ and $\delta^{13}C$ in pooled decapods species between the Pacific Halocline (<250 m) and the Atlantic layer (>250 m).

Persistent organic pollutants in Canadian Arctic seawater (Liisa Jantunen and team from ECCC and Toronto University)

- We developed trends for several persistent organic pollutants (POPs) in air and water over time at different locations in the Canadian Archipelago.
- Generally, the trends show that chemicals that have been banned are declining in air and water; chemicals that are still being used are remaining constant or increasing. As the climate in the arctic continues to change, the transport and fate of POPs to and within the arctic will also change. This research helps monitor those changes.
- This year we teamed with a researcher at the University of Toronto to investigate Microplastics pollution in the Canadian Arctic. Microplastics have some of the same characteristics of POPs. Evidence shows that microplastics are in the Arctic but little is understood about their sources, fate and extent of contamination.

RESEARCH OBJECTIVES

Hydrocarbons in Western Hudson Bay Sediments

- Identify the predominant sources of polycyclic aromatic hydrocarbons (PAHs), as well as characterise the profiles of organic carbon and redox elements within the sediment cores.

Hydrocarbons in Baffin Bay Sediment and Sea Stars

- Compare regional-level, baseline concentrations of PAHs in surface sediment and benthic organisms and bioaccumulation potential between different species in Baffin Bay and adjacent areas.

Interactions between oil and sea ice

- Identify and explain physical migration processes and chemical partitioning of crude oil in sea ice, as well as measure and model the geophysical and electromagnetic parameters of sea ice exposed to oil for the purpose of active microwave remote sensing (e.g. detecting oil in sea ice).
- Prioritize and communicate research and development activities to improve policy and practices dealing with oil spills in ice-covered Arctic waters.

Biogeochemical Cycling of Mercury in the Arctic Ocean and Hudson Bay

- To understand biogeochemical cycling of Hg, especially mercury methylation, in seawater and the sea ice environment in the Arctic Ocean including Hudson Bay.

Mercury and stable isotopes in decapods species, Beaufort Sea

- Determine contaminant and food web trends in the Beaufort Sea among various decapod (zooplankton) species.

Persistent organic pollutants in Canadian Arctic seawater

The short term objectives of this project are:

- to measures levels of persistent organic pollutants (POPs) in Canadian arctic air, water and zooplankton;
- to deploy passive water samplers in multiple locations in the Canadian Arctic;
- to screen for new and emerging compounds of concern in the Canadian Arctic;
- to provide environmental sampling training to a northern student;
- to determine the abundance and types of microplastics (MPs) in arctic air and marine ecosystems by sampling snow (as a surrogate for air), water, sediment and zooplankton from the Canadian Arctic; and
- assess the potential sources and fate of MPs in the Canadian Arctic.

Longer term objectives for this project are:

- to develop spatial and temporal trends for POPs and emerging compounds of concern in arctic air, water, sediment and zooplankton;
- to continue the passive water monitoring network on moorings in the Canadian Arctic and to be an on-going site for the AQUA-GAPS, a global passive water sampling network; and
- to use information gained from this study to inform: 1) whether we need to begin long-term monitoring for MPs in this region, 2) future observational and laboratory studies measuring the impacts of MPs to arctic wildlife and local communities and 3) contribute to building temporal and spatial trend data.

KNOWLEDGE MOBILIZATION

- Thirteen presentations (oral, poster) were offered at the Arctic Change 2017 conference.
- W. Armah and A. Gaden provided updates to the NGMP Secretariat with respect to Nunavut environmental monitoring projects.
- D. Chirkova and others will participate in Arctic Science Day 2018 at Fort Whyte Alive, Winnipeg, Manitoba, Canada (March 6, 2018) where they will have a crude oil spill (mesocosm) station for middle year students. The purpose will be to demonstrate remediation techniques and bring awareness of crude oil spills in the Arctic.
- A. Gaden, F. Wang, Z.A. Kuzyk and G. Stern completed the Contaminants chapter for the ArcticNet IRIS 3 (Hudson Bay) regional impact assessment (February 2018). The chapter summarizes the current state of knowledge of mercury and persistent organic pollutants in the marine ecosystem.
- F. Wang, A. Gaden and G. Stern contributed contaminants-related material for Chapter 9 of the "Expedition Churchill: Gateway to Arctic Research" multimedia, interactive e-book. Expedition Churchill is a major outreach project coordinated by the Centre for Earth Observation Science partnered with the University of Manitoba, Town of Churchill, Churchill Northern Studies Centre, VIA Rail Canada, Travel Manitoba, and Assiniboine Park Zoo – Journey to Churchill.
- F. Wang presented OSICA related activities at the 40th AMOP Technical Seminar on Environmental Contamination and Response (October 2017), and the 5th USA-Canada Northern Oil and Gas Research Forum (October 2017).
- L. Jantunen offered a presentation at the international Dioxin 2017 conference (Vancouver, Aug. 20-25, 2017).
- L. Jantunen gave a presentation at the NCP Results workshop in poster format and researcher exhibitor (Yellowknife, NTW, September 26-28 2017).
- J. Jantunen gave presentations to ECCC and University of Toronto researchers and students, and at the Nunavut Arctic College in Iqaluit and Aurora College in Inuvik.
- L. Jantunen authored and contributed to the 2017 AMAP Assessment of chemicals of emerging Arctic concern.
- G. Stern, F. Wang and L. Jantunen contributed metadata/data to the Polar Data Catalogue and the Environment and Climate Change Canada Data Catalogue.
- L. Jantunen collaborated with other arctic researchers: Terry Bidleman Umea University Sweden, Ashley Gaden UofM, Jennifer Provencher at Acadia University and Kyle Elliot of McGill U.
- L. Jantunen is involved with a collaboration with the University of Stockholm to determine volatile siloxanes in arctic sediments (manuscript is in preparation).

INTRODUCTION

Hydrocarbons in Western Hudson Bay Sediments

In recent years, industrial ship traffic through Chesterfield Inlet, NU has increased due to mining activities inland. Community members have expressed concerns about the potential for oil spills and impacts to food security and fisheries (e.g. Arctic Char and scallops) near town. In contrast, further north at Wager Bay, Ukkusiksalik National Park (UNP) has not experienced industrial ship traffic. However, mining activities outside the Park could lead to shipping through Wager Bay (UNP) waters at some point in the future. To prepare for this potential future shipping in Wager Bay (UNP) and address concerns about shipping through Chesterfield Inlet, Parks Canada Agency and the Government of Nunavut Fisheries and Sealing Division supported collection of sediment cores and baseline polycyclic aromatic hydrocarbons (PAHs) measurements in these two coastal environments. Here we present PAH profiles in four dated sediment cores collected across Chesterfield Inlet and Wager Bay (UNP) (Figure 1). We examined PAH composition to assess the importance of pyrogenic sources (combustion of wood or fossil fuels) vs. petrogenic sources (releases of petroleum hydrocarbons) (Yunker et al. 2002). We also describe geochemical properties of the sediments that inform us about depositional and post-depositional processes that affect PAH fluxes and profiles in sediments via biogeochemical cycles and microbial communities. Redox elements (manganese, iron, sulphur) buried in the seabed support organic carbon metabolism by responding to oxidation and reduction conditions.

Hydrocarbons in Baffin Bay Sediment and Sea Stars

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 baseline PAHs and the bioaccumulation potential in paired sediment and benthic invertebrate samples in various regions in and adjacent to Baffin Bay exhibiting distinct geological properties (Goni et al. 2013; Kuzyk et al. 2013). These six regions included the Nares Strait, North Water Polynya, Lancaster Sound, Peel Sound, West Baffin Bay and the West Greenland Shelf.

Interactions between oil and sea ice

Remote sensing has been used to assist in locating and tracking oil for forensic purposes for much time. However, difficulties in oil-in-ice and snow detecting

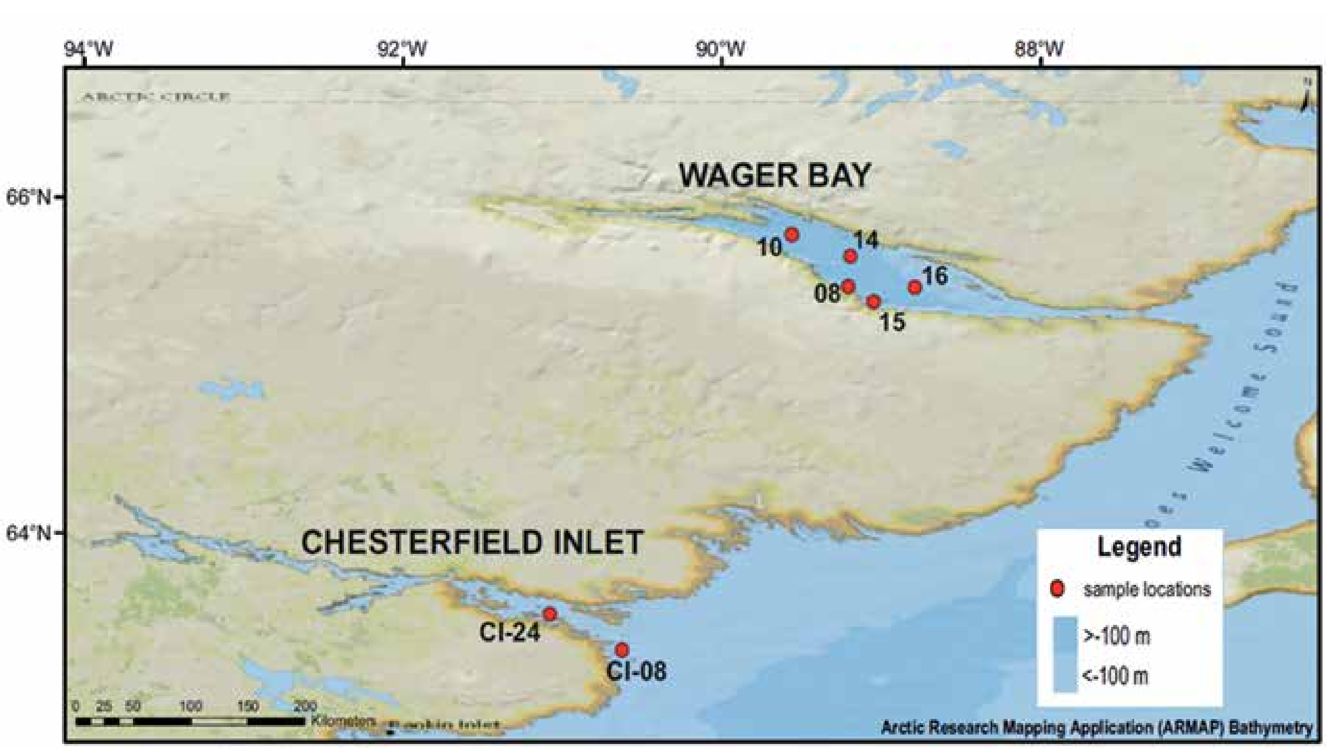

Figure 1. Sediment sampling stations at Chesterfield Inlet and Wager Bay, Nunavut.

are vast and require much further research; leading to only a few novel remote sensing technologies with potential for oil spill detection. In the event of a spill, the Arctic marine ecosystem will be affected by the presence and dispersion of petroleum hydrocarbons in which its behavior in the sea ice environment is not well understood. In order to further technologies for detecting crude oil spills in the Arctic, it is necessary fully grasp the physical and chemical processes and tendencies of oil in a sea-ice environment both on a macroscopic as well as a microscopic scale.

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.

Mercury and stable isotopes in decapods species, Beaufort Sea

Mercury is a major global pollutant that poses a risk to Arctic wildlife and the people in the region who depend on these animals for food. Mercury is a neurotoxin, particularly in the organic form of monomethyl mercury (MMHg) which accumulates in tissue. This study aims to establish baseline levels of total mercury (THg) and monomethyl mercury (MMHg) among three decapod species in the Beaufort Sea: *Eualus gaimardii*, *Sclerocrangon boreas* and *Sclercrangon ferox* (Figure 2), which were analyzed for THg, MMHg and $\delta^{13}C$ and $\delta^{15}N$ stable isotopes. Geographical considerations were factored into the analysis in order to better understand the food web structure within the region with respect to bioaccumulation and biomagnification of mercury.

Persistent organic pollutants in Canadian Arctic seawater

Air and biota monitoring results from the Canadian Arctic indicate that most legacy persistent organic pollutants including organochlorine pesticides (OCPs) such as DDT and hexachlorocyclohexanes (HCHs) and polychlorinated biphenyls (PCBs) are declining (Becker et al., 2012; Hung et al., 2010; Su et al., 2008; Ryan et al., 2013; Riget et al. 2010; AMAP, 2017). However, for some POPs (e.g., HCB, chlordanes) the rates of decline in air have slowed or levels have increased slightly in recent years (Hung et al., 2010; Ma et al., 2011; Becker et al., 2012). These increases have been attributed to climate change, which has increased surface air temperature and reduced ice cover, and thereby facilitates the release of contaminants from the water into the air. Future sampling would continue to follow this trend and develop trends for other compounds of interest.

Levels of per-fluorinated related compounds and polybrominated flame retardant (PBDEs) in seabirds, seals and beluga whales peaked in the late 1990s to early 2000s and are now declining (CACAR, 2013; AMAP, 2017). Declines in PBDEs have also been seen in air at Alert (CACAR, 2013; AMAP, 2017) probably as a result of bans and phase-outs in Europe and North America. Levels of hexabromocyclododecane (HBCDD), a PBDE replacement chemical, seem to be increasing in arctic char, lake trout, ringed seals and beluga (CACAR, 2013). Atmospheric deposition of deca-BDE onto ice caps demonstrates the importance

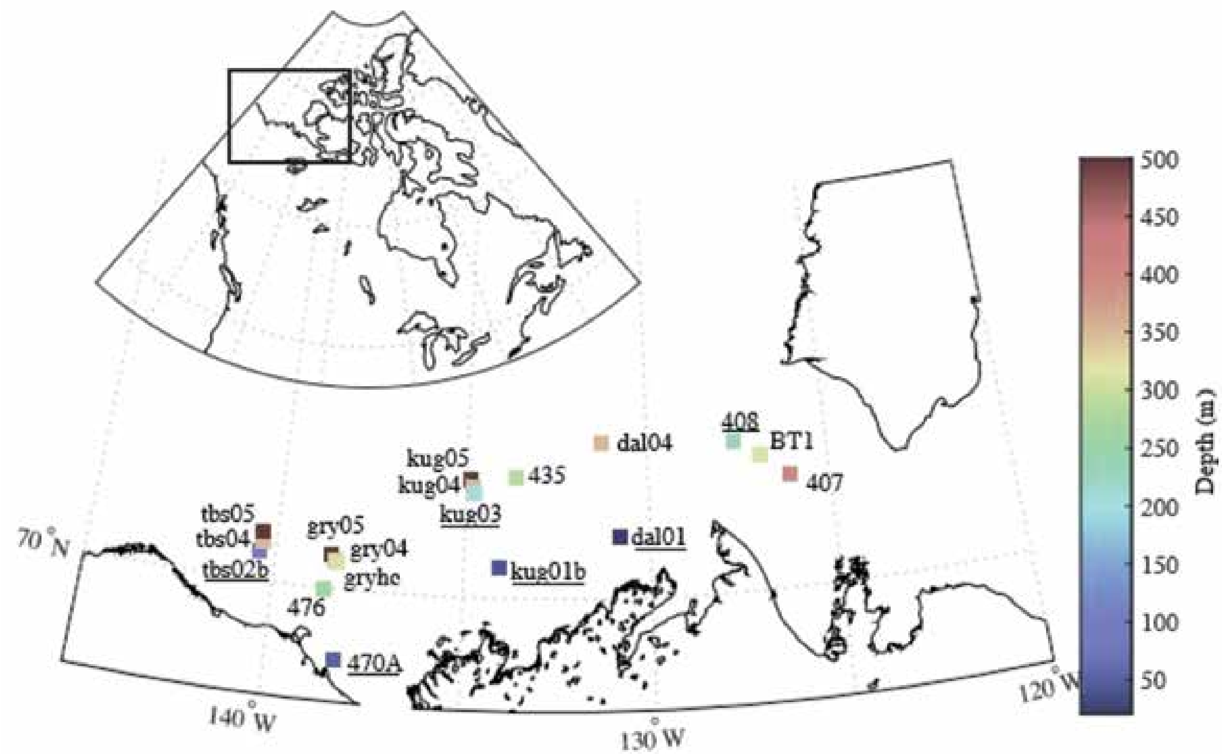

Figure 2. Stations sampled for decapods in the Beaufort Sea (2012-2014). Underlined stations indicate a depth <250 m. Map by Ryan Galley.

of particle transport (Meyer et al., 2012); this is also an important transport mechanism for heavier non-volatile polyaromatic compounds (PACs) and organophosphate esters (OPEs) which are largely particle bound. Monitoring replacement and new/emerging compounds is crucial to assess whether the next generation of compounds could pose a risk and to develop a case for national and international regulations before they become an arctic health hazard.

For water, only HCHs temporal and spatial trends exist: α-HCH and γ-HCH have declined and continue to decline in the Beaufort Sea and Canadian Archipelago (Pućko et al., 2013). Levels of other POPs and emerging compounds in arctic water are sparse and there is a large data gap for arctic contaminants. Such information is critical to evaluate the transport, fate and the relative contribution of ocean currents vs. the atmosphere for more water soluble chemicals such as CUPs, PFASs and potentially OPEs. PFASs have been found in arctic wildlife, and compared to chlorinated and brominated compounds, they are much more water soluble and accumulate differently in biota. Modelling of ocean currents and the presence of PFOS and PFOA in arctic seawater demonstrates the importance of oceanic transport (Armitage et al., 2009; Wania, 2007; Cai et al., 2012). Since some OPEs are also quite soluble, this transport mechanism may be a relevant pathway of exposure to arctic marine food chains. Seawater is a large slow-moving mass that will expose the Arctic to contaminants over the long term, hence levels may continue to increase for decades after they are banned (Lohmann et al., 2007; Gouin and Wania, 2007). Declines in air will eventually make an impact on POPs levels in biota, but there will be a lag time, especially for those chemicals that are delivered mainly via water currents (Lohmann et al., 2007). One example is β-HCH: it is delivered to the Arctic primarily through ocean currents, which has shown no decrease or may even be increasing in arctic biota in recent years (Addison et al., 2009; Lohmann et al., 2007). Deploying passive water samples on moorings will give us the opportunity to compare surface grab sampling with passive sampling. Additionally, the passive samples will be deployed at different depths in the water column so the extent of POPs contamination with depth can be assessed.

A major concern with POPs is their bioaccumulation and biomagnification potential, which results in high levels of some POPs in top predators, including humans. Traditional foods are often based on aquatic food webs, i.e., fish, whales and seals. Often, the consumption of fish, and marine mammals, is one of the main routes of POP exposure for humans (UNEP, 2003). Sampling POPs in the water column via passive water samplers will provide information on this reservoir, which is the basis for bioaccumulation. Additionally, longer term monitoring of POPs in water would provide crucial insight on whether reductions in primary emissions have resulted in reduced concentrations of POPs in arctic water and the lag time. As air concentrations of POPs continue to decline, oceans will buffer these declines by becoming secondary sources; this has been experimentally verified for HCHs (Jantunen et al., 2008; Wong et al., 2011, 2012) and predicted for other POPs (Becker et al., 2012; Ma et al., 2011; Nizzetto et al., 2010; Stemmler and Lammel, 2009). Finally, deploying passive water samplers at sites with parallel air sampling would make possible estimations of the direction and magnitude of fluxes due to gas exchange.

Many of the target compounds in this study are included in the Stockholm Convention and the Convention on Long Range Transboundary Air Transport (CLRTAP) lists of banned chemicals of which Canada is a signatory. Monitoring the levels of compounds in the environment is a part of the Stockholm Convention Global Monitoring Plan. Additionally, many of the new and emerging target compounds are on Canada's Chemical Management Plan priority compound lists or up and coming priority lists and/or have been identified by the Arctic Monitoring and Assessment Program (AMAP).

Microplastics (MPs) contaminate the oceans from the poles to the equators and from the sea surface to the deep sea (GESAMP 2016). In addition, MPs have been recorded in freshwater systems, including in lakes, rivers and streams globally (Eerkes-Medrano et al. 2015, Ballent et al. 2016). Hundreds of studies document concentrations of MPs in samples from across the globe, and therefore, for most regions, the presence of the contamination is less important than potential sources, transport pathways, fate, and impacts. MP debris has been identified as a global pollutant of concern that is capable of long-range transport and can cause adverse effects in wildlife. Microplastic pollution is a field of intense interest globally, but limited information is available for Canadian arctic regions. Consequently, the Arctic Monitoring and Assessment Programme (AMAP) has also added Marine Plastics and MPs to their list of Chemicals of Emerging Arctic Concern.

ACTIVITIES

Hydrocarbons in Western Hudson Bay Sediments

Diagnostic ratios (Yunker et al. 2002) and principle components analysis (PCA) were performed on the PAH data derived the previous year on western Hudson Bay sediment samples. Total organic carbon (TOC) was analyzed at the Stable Isotope Lab at the University of Manitoba while redox-sensitive elements (Mn, S, Fe) were analyzed at ACME Labs (Bureau Veritas, Vancouver).

Hydrocarbons in Baffin Bay Sediment and Sea Stars

We applied diagnostic ratios detailed in Yunker et al. (2002) and Stogiannidis and Laane (2015) to determine sources of PAHs in sediment. Principle component analysis (PCA) models were conducted on concentrations and compositions of PAHs across sediment and sea star samples to determine overlying trends and associations with site characteristics.

Interactions between oil and sea ice

Following up from the oil-in-sea ice mesocosm experiments conducted at the University of Manitoba Sea-Ice Environmental Research Facility (SERF), January-March 2016 and February-March 2017, we compiled and analyzed the data captured from thermocouple (temperature), ice core sampling (bulk salinity, hydrocarbons (see next paragraph) and oil distribution/volume via X-ray microtomography) and microwave (NRCS) measurements of both uncontaminated and oil-contaminated sea ice. Then, using several models, we modelled the complex permittivity profile of ice to simulate the NRCS of the ice, both in the presence and the absence of oil. Models used our experimental (1) physical observations and (2) results of the X-ray microtomography scans.

Chemical analysis of the crude oil, taken spatially and temporally within the ice, was conducted using Gas chromatography time-of-flight mass spectrometry and Triple Quadrupole Gas Chromatography-Mass Spectrometry. The composition of the crude oil was found to be a mixture of n-alkanes, trimethylalkanes, isoprenoids, alkyl cyclohexanes and their methyl substituted analogues, alkyl cyclopentanes, n-alkylbenzenes, methyl alkylbenzenes, aryl isoprenoids with methyl substitutions at 2,3,6 and 3,4,5 positions at the aromatic ring, decalins, naphthalenes, phenanthrenes, biphenyls, methylbiphenyls, dibenzothiophenes, dibenzofurans, steranes and terpanes.

Finally, as a new component of our research (conducted in the first quarter of 2018), our group designed, prepared and conducted a crude oil in sea ice mesocosm experiment with the water inoculated with authentic Arctic bacteria. These bacteria were collected at Cambridge Bay in August 2017 which was enriched in artificial seawater in the dark at 4°C with 0.1% crude oil. The main goal of this research is to evaluate the bacterial impact on crude oil change in an Arctic environment. This study is still underway and results are not yet available.

Biogeochemical Cycling of Mercury in the Arctic Ocean and Hudson Bay

- Sampling of the Hudson Bay marine system was cancelled due to the cancellation of the CCGS *Amundsen* cruise.
- Sampled the Churchill and Nelson River estuaries and numerous lakes in the Nelson River Basin.
- Completed the analysis of samples collected from previous years.

Mercury and stable isotopes in decapods species, Beaufort Sea

Archived decapods from sites sampled along CCGS *Amundsen* expeditions (2012-2014) were analyzed for THg in tail muscle tissue samples. Samples were dissected prior to freeze drying and analysis was done using cold vapor atomic absorption spectrometry (CVAAS) at the University of Manitoba. Bulk, dissected tail muscle shrimp samples were used for the MMHg analysis. The methods were based on the Brooks Rand alkaline digestion of biological tissue and the EPA Method 1630. Isotopes of C and N were analyzed by Isotope Ratio Mass Spec in the lab of Jean-Éric Tremblay by Jonathan Gagnon.

Persistent organic pollutants in Canadian Arctic seawater

During the summer of 2017, ArcticNet activities included sampling from the CCGS *Amundsen* the Hudson Bay and the Canadian Archipelago (Legs 1 and 2b) and the Laurier in the Beaufort Sea. A summary of these field samples and analytes is provided in Table 1.

Table 1. Samples collected for specific analytes, the volume and the number collected from both the CCGS Amundsen (A) and the Laurier (L) in the summer of 2017 as part of our ArcticNet-funded research.

Media Collected	Analytes of interest	Volume Collected - Number of samples collected (A: Amundsen, Leg 1 and 2b and L: Laurier Beaufort)
Sediment, surface	• Organochlorine pesticides, current use pesticides, siloxanes, perfluorinated compounds, organophosphate esters and flame retardants • Micro and nano-plastics	150mL- 23 (A leg 1 and 2b) 150mL- 19 (A)
Water, surface	• Organophosphate Esters • Organochlorine pesticides and current use pesticides, polycyclic aromatic hydrocarbons • Micro and nano-plastics	4L- 16 (A) and 6(L) 100L- 8 (A) and 8(L) 20L- 25 (A)
Water, surface and several depths	• Perfluorinated Chemicals	1L- 18 (A)
Air, continuously running on the bow	• Organochlorine pesticides, polycyclic aromatic hydrocarbons, current use pesticides, and flame retardants	1000m3 – 10 (A) and 10 (L)
Water, surface particulate	• Organochlorine pesticides, current use pesticides, polycyclic aromatic hydrocarbons and flame retardants	1000L- 7 (A)
Passive samplers - Annual	• Organochlorine pesticides, polycyclic aromatic hydrocarbons, current use pesticides, and flame retardants	Amundsen: • 2 sets retrieved • 2 sets Deployed Laurier • 6 sets retrieved • 7 sets deployed
Zooplankton	• Microplastics	11 zooplankton samples (A)

RESULTS

Hydrocarbons in Western Hudson Bay Sediments

PAH sources assessed using diagnostic ratios and principal components analyses (PCA) imply dominance of pyrogenic sources (i.e. combustion) (Yunker et al. 2002). This is also illustrated in Figure 3a whereby pyrogenic compounds on PC1 account for 40% of the variability in the data compared to 17% on PC2, which plots mostly petrogenic compounds. There is some separation between Wager Bay and Chesterfield Inlet samples on PC2, which implies some subtle regional differences (Figure 3b).

Total organic carbon (TOC) fell within the range of 0.75%-1.93% among sediment cores. Across all cores, TOC decreased with depth, implying TOC oxidation (Macdonald et al. 2008). With respect to redox elements, iron and sulphur increased with depth at all locations, implying strong reducing conditions in subsurface sediments. Manganese profiles, however, decreased with depth in two cores (one from Wager

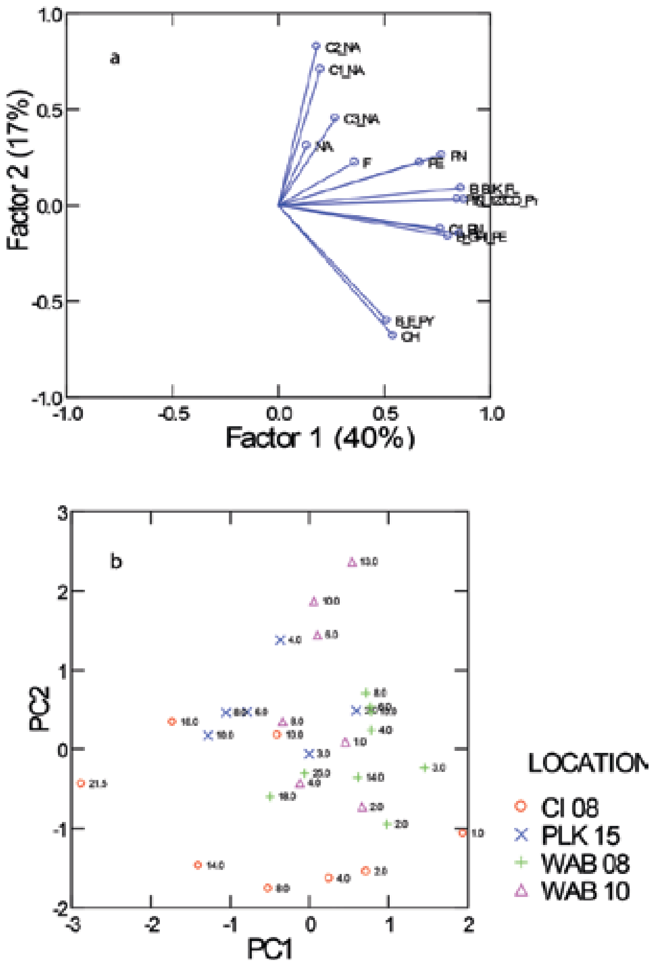

Figure 3. Principle components analysis (PCA) of 15 polycyclic aromatic hydrocarbons (PAHs) in Chesterfield Inlet (CI 08) and Wager Bay (PLK 15, WAB 08, WAB 10). The factor loadings plot in (a) illustrates several high molecular weight, pyrogenic-sourced PAHs along PC1, including pyrene (PN), indeno(1,2,3-c,d)pyrene (IN_123CD_Py), benzo(ghi)perylene (B_GHI_PE), and benz(b,j,k)fluoranthene (B_BJK_FL). The factor scores plot in (b) shows the various sediment core depth slices from which PAHs were analyzed (e.g. 13.0 = 13.0 cm depth).

Bay, one from Chesterfield Inlet), implying oxic conditions in the surface sediment and reducing conditions in subsurface sediment. The remaining cores from Wager Bay illustrated no change throughout their profiles, indicating that the sediments exhibited reducing conditions.

Hydrocarbons in Baffin Bay Sediment and Sea Stars

The alkylated to parent ratio, a robust measure over large distances and time spans (Stogiannidis and Laane 2015), indicated that all stations were predominantly petrogenic-sourced. Sediment PCAs grouped all but two Polynya stations together, which were associated with the heavier molecular weight PAHs (e.g. benz(a) anthracene to benz[g,h,i]perylene). This is illustrated in Figure 4 whereby Polynya stations are plotted on the left PC1 axes. Here, PC1 scores were weakly, significantly related to sediment $\delta^{13}C$ ($r= -0.55$, $p=0.022$) and total organic carbon ($r= -0.5$, $p=0.034$), which was not unexpected for Polynya stations.

With respect to the sea stars, within the North Water Polnya (the region with highest sample abundance) we did observe the sediment-ingesting *Ctenodiscus crispatus* contained marginally higher, yet significant, proportions of perylene (a naturally occurring PAH in sediment; ANOVA $F_{3,20}=3.33$, $p=0.040$) compared to the predatory/scavenging *Ophiopleura borealis*. Principle components analysis indicated no significant differences between species, regional or Polynya vs non-polynya differences in PC1 or PC2 scores.

Finally, in applying a biota-sediment accumulation factor (BSAF) across all paired species and sediment samples, we noticed there was generally no bioaccumulation of PAHs from sediment to sea stars, indicating either metabolism or reduced bioavailability of PAHs by the sea stars. A PCA of the BSAFs revealed several interesting regional-level contrasts (Figure 5). In general, BSAFs were highest in NOW stations, followed by Lancaster Sound, and West Baffin and Nares Strait. Compared to Lancaster Sound stations, BSAF values for all PAHs were generally higher at NOW except for napthalene and pyrene.

Interactions between oil and sea ice

The crude oil was injected underneath 6 cm thick sea ice and was encapsulated within 2 days (Fingas and Hollebone 2003). After continued ice growth, the

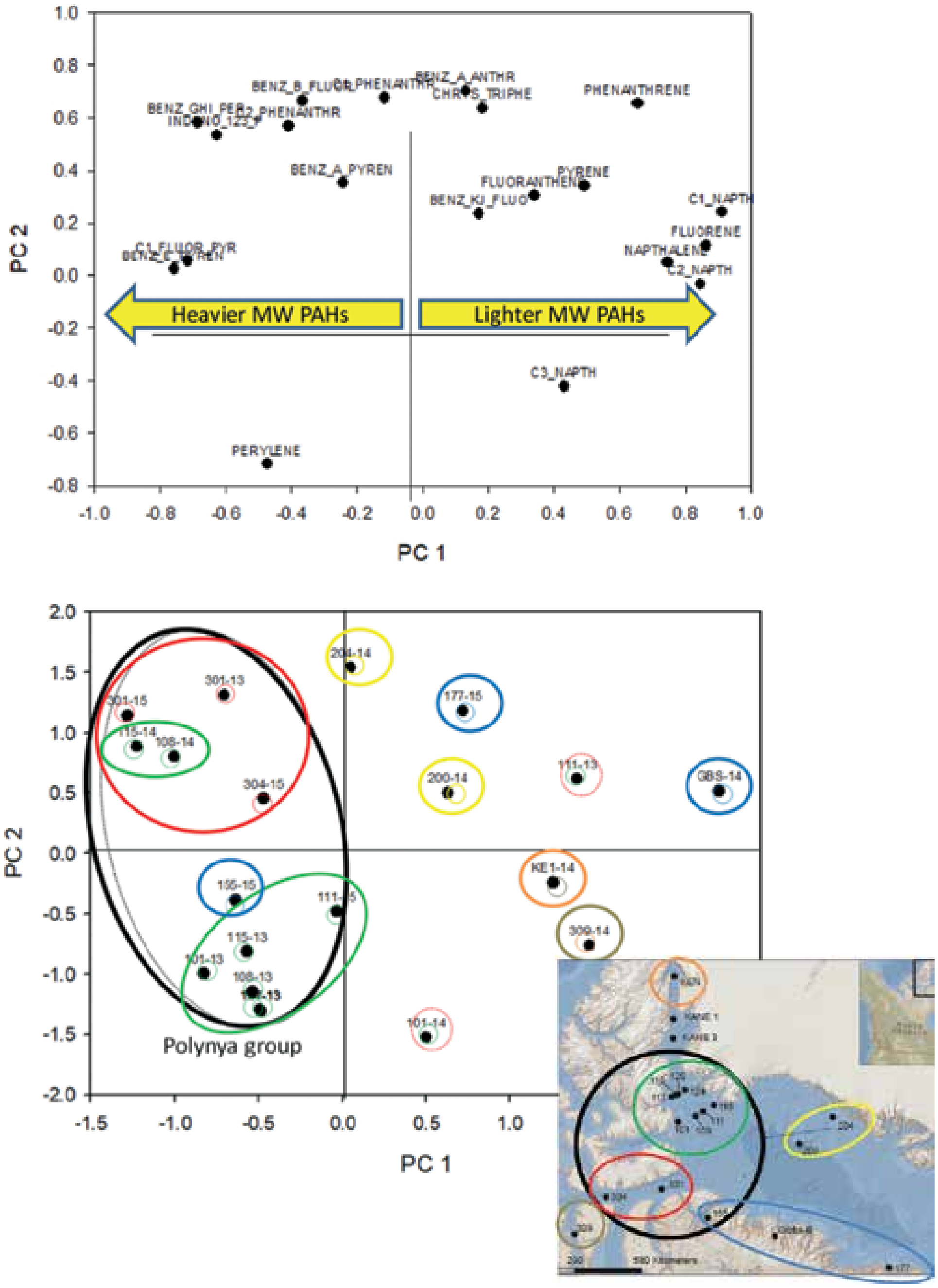

Figure 4. PCA correlation matrix of 20 PAHs in sediment samples collected between 2013-2015 across Baffin Bay and adjacent regions. The PCA uses compositional data (i.e. PAH/total PAHs). PC1 and PC2 account for 32% and 22% of the variation, respectively. The Polynya stations, outlined with a black ellipse in the bottom panel, appear to be associated with heavier molecular weight (MW) PAHs (top panel), and their PC1 scores are significantly different than non-polynya PC1 scores (t=3.33, p=0.004). Two North Water Polynya (NOW) stations which do not follow this association are 101-14 (suspected to have naphthalene contamination) and 111-13 (peculiar PAH signature possibly due to an oil seep; Foster et al. 2015). Station 155-15, originally a West Baffin station, was plotted in the Polynya group, suggesting similar PAH sources as the polynyas.

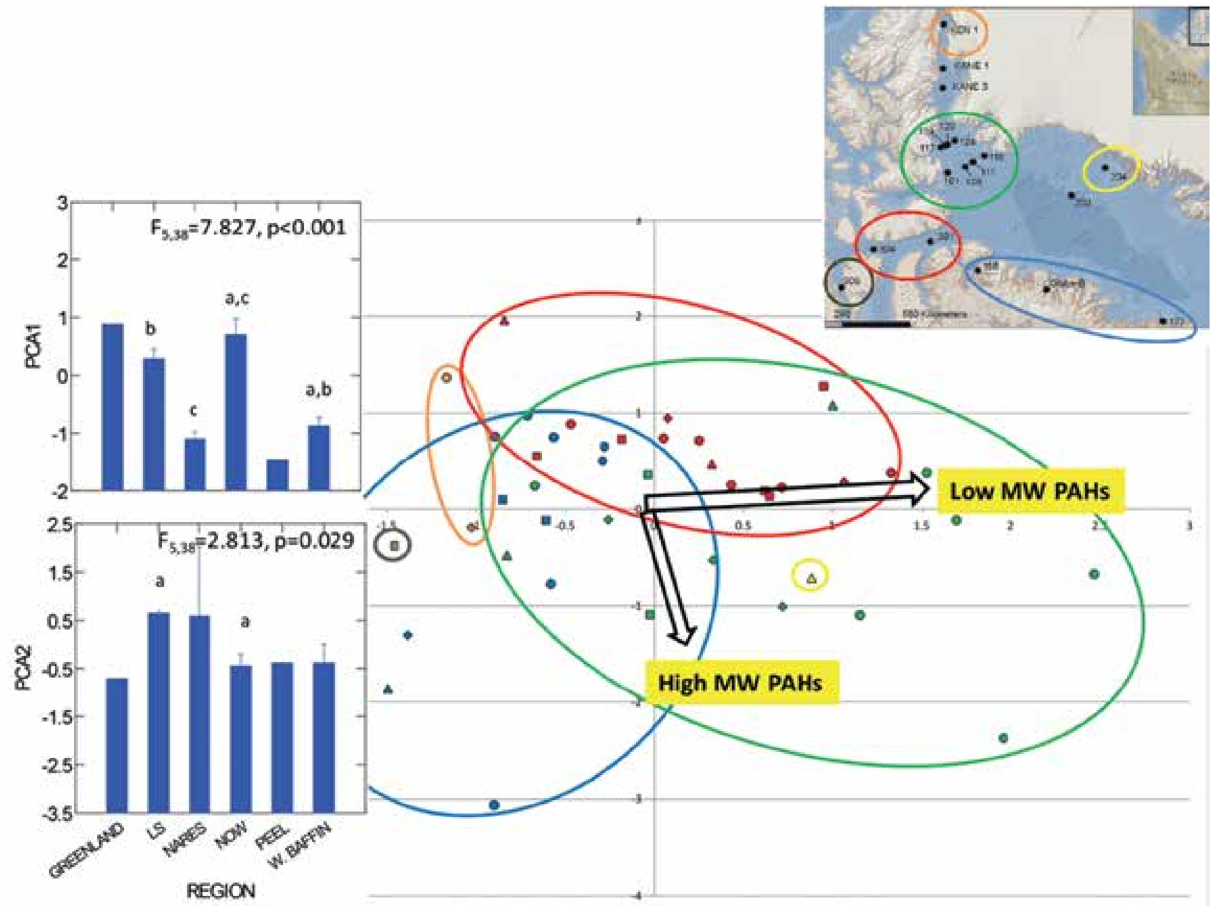

Figure 5. PCA (factor scores only) and bar plots with ANOVA statistics and post-hoc Tukey test comparisons (paired letters denote significant differences between regions) for regional comparison of biota-sediment accumulation factors (BSAFs) in the Baffin Bay area. PC1 and PC2 accounted for 48% and 12% of the variability, respectively. Although BSAFs generally indicated no bioaccumulation of PAHs between sediment and sea stars across Baffin Bay, the North Water Polynya (NOW) (green) and Lancaster Sound (LS) (red) tended to have the highest values, followed by West Baffin (blue) and Nares Strait (orange). In comparing PC1 scores regionally, West Baffin sites were significantly different than those in Lancaster Sound and NOW, as were NOW sites with Nares Strait sites. Looking at PC2 scores, only NOW and Lancaster Sound sites were significantly different.

majority of the oil was found encapsulated around the oil introduction point (6 cm) on day 8. In contrast, on day 13 most of the crude oil migrated onto the ice surface showing potential for upward migration. Additionally, crude oil was found below the oil introduction point (6 cm) providing evidence of downward migration. Not surprisingly, the chemical composition of the oil around the oil introduction point was found to be the closest to the technical oil mixture. Crude oil which migrated upwards or downwards lost most of its low molecular weight components and its partitioning between the top and bottom became more significant over time. A photo montage of the oil-in-sea ice experiment is provided in Figure 6.

It was observed that the presence of crude oil significantly affected sea ice temperature and caused melting of the snow cover on the ice surface and impeded the growth of sea ice. The complex permittivity of the crude oil itself decreased overtime and the complex permittivity of the sea ice was lowered with greater amounts of oil. This was expected, since oil-contaminated ice is less saline (less brine) and oil within the ice also has the lowest permittivity of all the components of the ice (i.e. air, brine, ice). In the permittivity models, in most cases, temperature was the most sensitive variable, although this was sometimes frequency and oil volume fraction (Neusitzer et al. 2018).

Sea ice consolidation, with the presence of crude oil in the water-air interface, started with the formation of individual ice floes. Consequent grounding of the ice floes together with saturated crude oil squeezed between their interstices led to the formation of pancake ice with a non-homogeneous surface and liquid lenses of crude oil in the top section of the ice, which was also observed previously by Buist and Dickins (1987).

Biogeochemical Cycling of Mercury in the Arctic Ocean and Hudson Bay

High resolution profiling of MeHg revealed that the major sub-surface peak in MeHg in the Canadian Arctic was primarily associated with the Pacific halocline waters. Elevated MeHg concentrations were also found at depth of subsurface chlorophyll maximum and in a few locations in the surface water.

Figure 6. Above photos illustrate a multidisciplinary study of crude oil behavior in a sea ice environment which took place at the Sea-Ice Experimental Facility (SERF)'s oil pool during January – February 2017 (similar oil-in-sea ice experiments are occurring Jan-March 2018). A light crude oil was injected underneath young sea ice. The ice was sampled during the month with state-of-the-art analytical chemistry instrumentation at the University of Manitoba's Petroleum EnvironmenTal Research Lab (PETRL), providing spatial and temporal mapping of the oil composition. Right pictures demonstrate the pool's evolution: the top photo was taken a week after oil addition, the central photo illustrates the pool appearance after the first core samples were taken, and the bottom photo depicts the influence of the crude oil's presence on the ice structure. (Photos by D. Chirkova and D. Desmond, University of Manitoba. Caption by D. Chirkova.)

Concentrations of Hg and MeHg in four lakes in the Nelson River systems of the Hudson Bay watershed were generally low. The mechanism of the sub-surface production of methylmercury remains to be elucidated. Large differences in total mercury (THg) profiles are observed from sediment cores taken from lakes in the Nelson River Watershed. Compilation of atmospheric elemental mercury (Hg0) concentrations measured throughout the ArcticNet cruises generates the spatial distribution pattern of Hg0 in coastal waters of circum-North America (from tropical to Arctic regions, 6.7 °N to 77.3 °N), as well as seasonal distribution pattern in the Amundsen Gulf region of the Arctic. The data are being compared with the results from the global chemical transport model.

Mercury and stable isotopes in decapods species, Beaufort Sea

S. ferox had the highest mean levels of THg (1.4±0.6 μg/g) and MMHg (1.7±0.4 μg/g), while *E. gaimardii* had the lowest (0.5±0.3 μg/g and 0.4±0.2 μg/g, respectively). Mean proportions of MMHg of THg ranged from 60% in *E. gaimardii* to 100% in *S. ferox*, indicating that *S. ferox* tends to accumulate MMHg to a much greater extent. *S. ferox* also exhibited the most enriched $\delta^{13}C$ levels (-19.4±0.6‰) whereas *S. boreas* showed the most depleted $\delta^{13}C$ levels (-21.0±0.9‰) and highest $\delta^{15}N$ levels (16±1‰). *E. gaimardii* occupied the lowest trophic level with mean $\delta^{15}N$ levels of 14±1‰. For *S. ferox* only, $\delta^{13}C$ exhibited a significant linear regression with longitude (r^2=0.969, $p<0.001$). Finally, when species were pooled, we observed a statistically significant difference between the THg, MMHg, $\delta^{15}N$ and $\delta^{13}C$ data <250 m and >250 m ($<0.001 <$ p-value < 0.020) between depths <250 m (Pacific Halocline) and >250 m (Atlantic layer).

Persistent organic pollutants in Canadian Arctic seawater

Air Samples

Chemicals banned by national and international regulators such as organochlorine pesticides are declining (Figure 7 show levels of α-hexachlorocyclohexane (α-HCH) in air between 1992-2016, of which 2007-2016 are taken from the *Amundsen*). The levels in air are now approaching detection limits so the volume of air collected in 2017 was increased to increase our detectability.

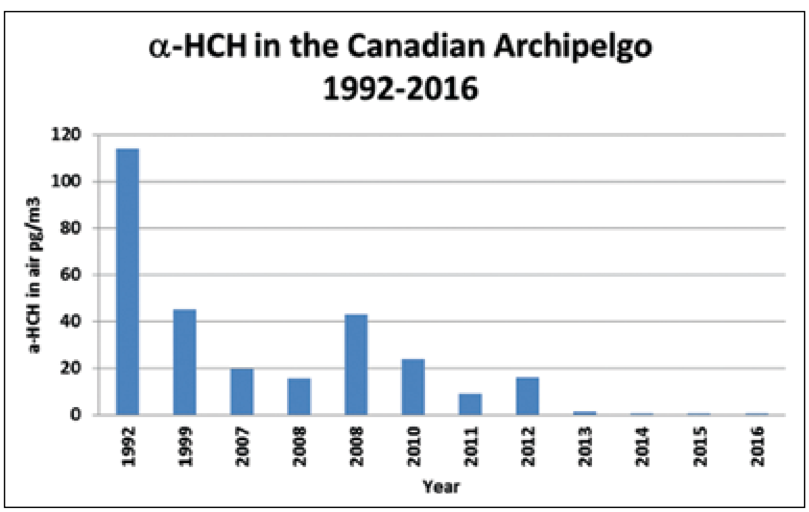

Figure 7. Declining levels of a national and internationally banned organochlorine pesticide, α-HCH (pg/m³).

Levels of organophosphate flame retardants and plasticizers are increasing over time, but the levels are variable (Figure 8). Additionally, the number of OPE compounds with >50% detection rates are also increasing, i.e. ethyl-hexyl-diphenyl phosphate (EHDPP) and tri-cresyl phopshate (TCP) were not detected in samples prior to 2010 but are now found in 50-100% of the samples, depending on the sampling year, (see Figure 8 and see figure footnote for the compound names). Samples taken in Resolute Bay in 2012 show high levels of tri-n-butyl phosphate (TnBP); this is probably from a local source, the airport, as TnBP is the primary ingredient in airplane hydraulic fluid. TnBP is also seen to a less degree in samples from Svalbard. In 2013 there was a spike in the tri-phenyl-phosphate (TPhP) concentrations from on board the *Amundsen*, but the reason for this is unknown. Additionally in 2016, there was a spike in concentrations in tris-chloroethyl phosphate (TCEP), reasons are also unknown.

Passive water samples

This year, one mooring in the Beaufort Sea was lost and along with it one passive sampling cage. We were able to retrieve and redeploy at all other sites in the northern Davis Straight, near Cambridge Bay and the Beaufort Sea (Figure 9). In five out of 10 of our passive sampling cages, AQUA-GAPS passive strips were also deployed (Lohmann et al., 2017).

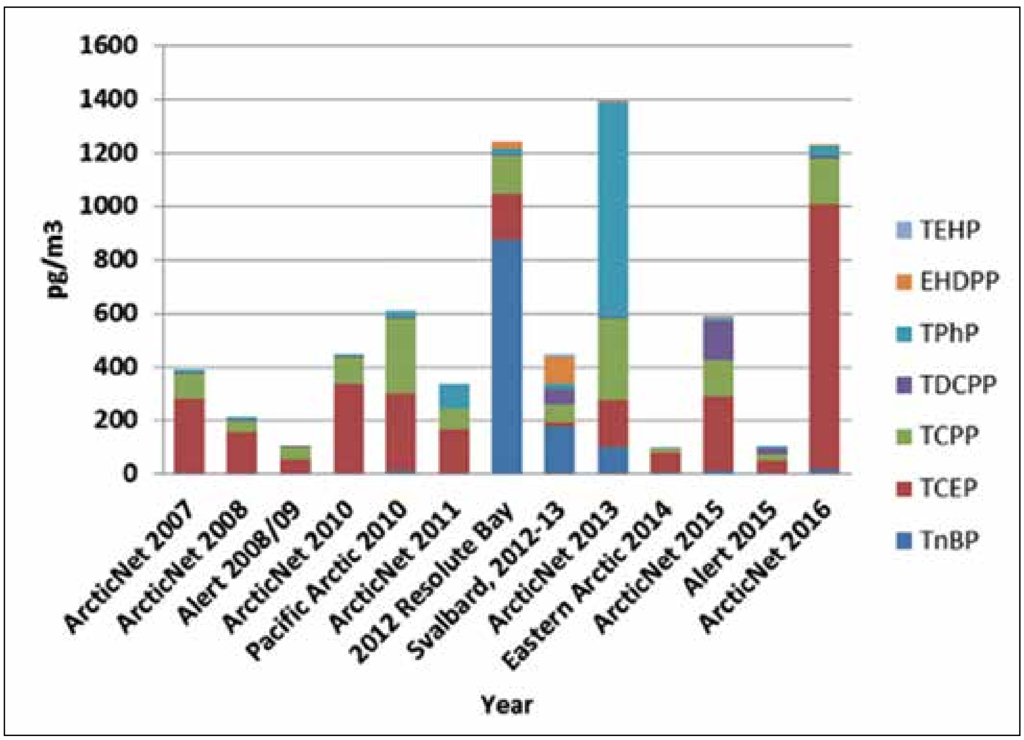

Figure 8. OPEs in air 2007 to 2016 from all sources. References: ArcticNet 2007-2013: Suhring et al., 2016; ArcticNet 2014-2016, 2012 Resolute Bay and Alert: Jantunen et al., unpublished data; Pacific Arctic 2010: Möller et al., 2012 and Eastern Arctic 2014: Li et al., 2017. OPE names: tris(2-chloroethyl) phosphate (TCEP), tris(1,3-dichloro-2-propyl) phosphate (TDCPP), triphenyl phosphate (TPhP), tri-n-butyl phosphate (TnBP), tris(1-chloro-2-propyl) phosphate (isomers TCiPP and TCPP2), tris-2-butoxyethyl-phosphate (TBEP), ethyl-hexyl-diphenyl phosphate (EHDPP), tris-2-ethylhexyl-phosphate (TEHP), tris-cresyl phosphate (ortho, meta and para isomers, TCP), tris(2-isopropyl phenyl) phosphate (T2iPPP).

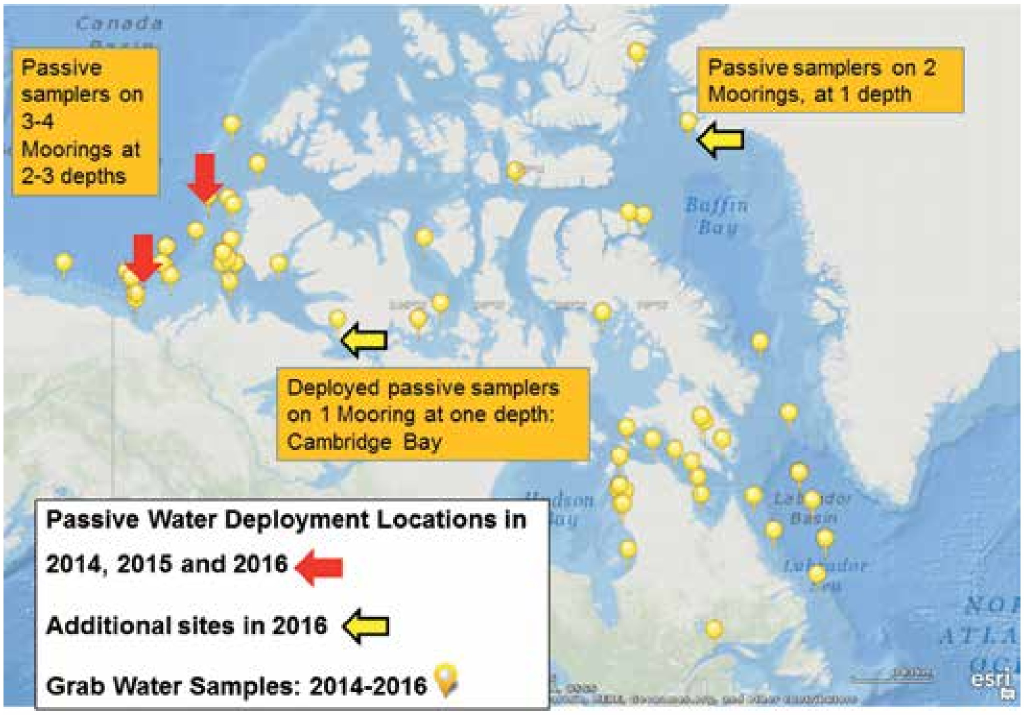

Figure 9. Map of passive sampler deployment locations.

Grab Surface Water Samples

Grab surface water samples were collected for organophosphate esters (OPEs) (see Figure 10, where the bars are organized by increasing salinity). The relative composition of the water samples are all similar and dominated by TCEP. Although there are some differences, the first sample is highly influenced by melting ice and snow indicated by the lowest salinity (and it had the coldest water temperature), and it also has a higher proportion of TPhP. TPhP is less volatile than other compounds and may be preferentially scavenged in the rain and snow and released when melting. The more volatile OPEs such as TCEP and TCPP also showed a significant correlation with longitude but not latitude with higher concentrations in the west compared to the east. This may be due to Beaufort waters being influenced by higher levels in waters that originate in Asia, a high consumer of flame retardants and plasticisers (Moller et al., 2012). Eastern waters, however, are influenced by lower level Atlantic waters. This same trend is seen for α-HCH (Bidleman et al. 2007).

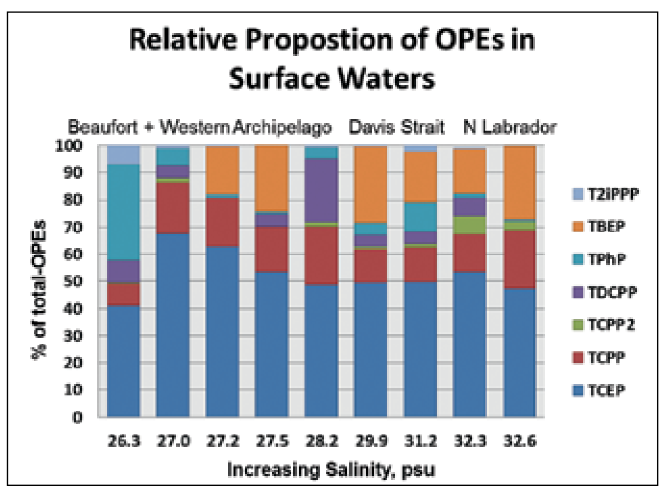

Figure 10. Relative percentage of OPEs in surface water from all regions of the Canadian Archipelago.

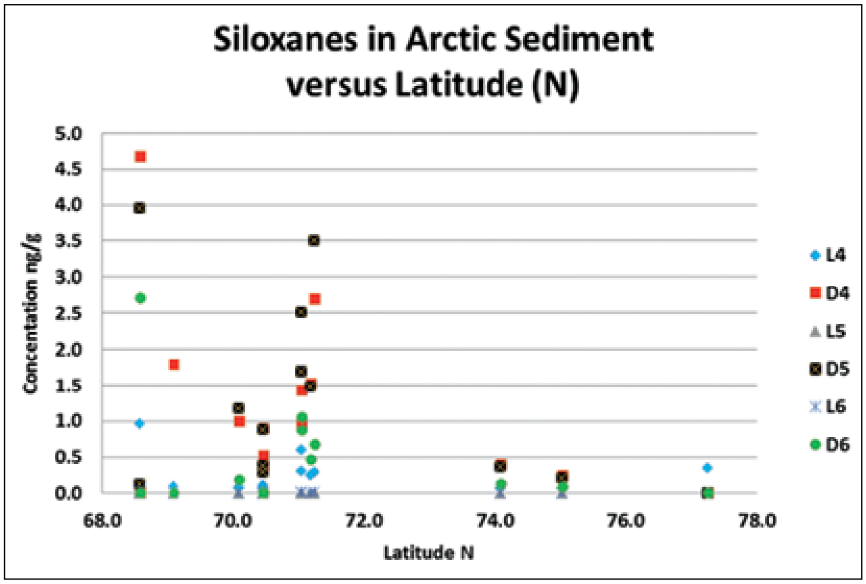

Figure 11. Siloxane concentrations in archived sediments (2014-2015).

Sediment Samples

Archived sediment samples from 2014-2015 were analyzed for the cyclic and linear volatile methylsiloxanes (Figure 11). Compounds sought included octamethylcyclotetrasiloxane (D4), decamethylcyclopentasiloxane (D5), dodecamethylcyclohexasiloxane (D6), decamethyltetrasiloxane (L4), dodecamethylpentasiloxane (L5) and tetradecamethylhexasiloxane (L6). Concentrations of L5 were below detection limits in all samples where all other compounds were found in most samples. Levels of siloxanes declined with latitude but have no correlation with the organic carbon-water partition coefficient (KOC) (Panagopoulos et al., 2017).

DISCUSSION

Hydrocarbons in Western Hudson Bay Sediments

Overall high molecular weight PAHs are higher than the low molecular weight PAHs in both Chesterfield Inlet and Wager Bay (UNP) cores, suggesting that PAH sources are locally transported or are reflecting background *in situ* concentrations (Hung et al. 2005).

Hydrocarbons in Baffin Bay Sediment and Sea Stars

Although all sites are petrogenic-sourced, we suspect that higher downward carbon fluxes in the NOW and Lancaster Sound polynyas are influencing the relatively higher concentrations of high molecular weight PAHs in those regions. High molecular weight PAHs tend to bind to organic particulate matter, thus areas with high productivity, such as polynyas, may be subject to higher scavenging processes.

Interactions between oil and sea ice

The buoyancy of the crude oil owing to its low density compared to brine allowed for upward movement towards the sea ice surface where it was subjected to weathering processes. According to the data obtained from the 2016 experiment, crude oil lost 18.8% of the identified components due to evaporation which explains a depletion of low molecular weight compounds in the top sections of the ice. Furthermore, a depletion of low molecular weight components in both the bottom and top sections of the ice can be attributed to dissolution via downward migration in which melting of the sea ice provided a solvent for both encapsulated and surfaced crude oil transporting it down into the water column through an opened brine network (Faksness et al. 2008).

The presence of the crude oil at the ice surface significantly influenced the temperature of nearby ice and snow, primarily due to absorption of sunlight (decreased albedo) (Glaeser and Vance 1971), thereby allowing for the potential for early melting (NORCOR 1975). Due to the increased temperature of the ice as well as a decreased albedo, melting of snow ensued at areas with high oil contamination. The snow was found to be thicker near the cleanest sites where the concentration of oil is low and vice versa. The high influence of crude oil presence on temperature aided the formation of pancake ice with a non-homogeneous surface in the experiment when the crude oil was in the water before the ice started to form. Overall, a loss of volatile crude oil components at the sea ice surface led to a decrease in the complex permittivity of the oil which facilitated a further enhanced decrease in the complex permittivity of the sea ice, detectable by remote sensing techniques. In evaluating the various permittivity models, clear differences were noticed in response to changes in temperature and oil volume fraction, and it was undetermined if one model was superior to the rest (full details in Neusitzer et al. 2018).

Biogeochemical Cycling of Mercury in the Arctic Ocean and Hudson Bay

Our finding of a ubiquitous sub-surface enrichment of MeHg in the Canadian Arctic Ocean could be significant in understanding Hg bioaccumulation in Arctic marine ecosystems. Efforts are needed to elucidate the processes that are responsible for such sub-surface MeHg enrichment. Mass budget studies of methylmercury in Hudson Bay are delayed due to the cancellation of the CCGS *Amundsen* cruise in 2017, but evidence is mounting that methylmercury concentrations in Hudson Bay ecosystems are affected by both hydroelectric development and a changing climate.

Mercury and stable isotopes in decapods species, Beaufort Sea

In general, mean levels of THg, % MMHg and δ^{15}N levels increased from smaller decapods species (*E. gaimardii*) to larger decapods (*S. boreas* and *S. ferox*). *S. ferox* exhibited the highest THg, MMHg, % MMHg and δ^{13}C levels. This was also the only zooplankton species to show any association with longitude, which has been documented with zooplankton in the Beaufort Sea previously (Dunton et al. 1989; Saupe et al. 1989). Furthermore, the statistical difference among THg, MMHg, δ^{15}N and δ^{13}C levels between shallow (<250 m) and deep (>250 m) depths implies that water mass has an influence on these variables.

Persistent organic pollutants in Canadian Arctic seawater

Levels of banned compounds, including organochlorine pesticides, polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs) and some perfluorinated compounds, are decreasing. Compounds in current usage are increasing or remaining level in the Arctic. These same trends are found in air, water and biota throughout the Arctic (AMAP, 2017). A comparison of OPE levels in the Arctic is give in Figure 8. Levels found here are similar with other groups but there are some differences and local sources are suspected.

As the climate continues to change in the Arctic, these downward trends of banned compounds may be disrupted (AMAP, 2017). Due to the cold temperatures in the Arctic, these semi-volatile organic compounds tend to accumulate in the arctic environment and the ice cap prevents these compounds from volatilizing from the water into the air. With less ice, these chemicals have the potential to be released and the Arctic can become a second source. This has been seen for α-HCH (Wong et al., 2012).

Although the results are preliminarily, microplastics (MPs) were found in all samples taken in the Canadian Archipelago in the summer of 2017, confirming other studies that state MPs ubiquitous in our environment. Generally the MPs were fibers and were ~500 µm and smaller within sediments.

CONCLUSION

Hydrocarbons in Western Hudson Bay Sediments

We have identified sources (local/pyrogenic) and geochemical controls of petroleum hydrocarbons in arctic sediments in the Kivalliq region of Nunavut. During the next few months, final activities for the completion of this sub-project will include the (1) analysis of n-alkanes concentrations and sources and (2) integration of PAH and metals data with sedimentation rates.

Hydrocarbons in Baffin Bay Sediment and Sea Stars

Results indicate that geography is the most important factor for PAH concentration and BSAF value variation among Baffin Bay marine sediments and benthic invertebrates. A manuscript for this sub-project is well underway and we expect it to be submitted before the 2018 field season.

Interactions between oil and sea ice

Data analyzed from experiments conducted during 2016 and 2017 is crucial for the understanding of crude oil behavior in a sea ice environment. The observed changes in the crude oils composition and the resultant effect it had on the physical properties of the ice can be used for the development of remote sensing technologies for detecting crude oil spills in Arctic environments.

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. Future studies should focus on coupling climate models with mercury transport and biogeochemical models to allow projection of how Arctic marine ecosystems respond to a changing climate and to economic development (e.g., marine shipping, hydroelectric development).

Mercury and stable isotopes in decapods species, Beaufort Sea

Decapod size and species and water mass were shown to affect mercury and stable isotope signatures in the Beaufort Sea ecosystem. The data is being prepared into a manuscript for publication.

Persistent organic pollutants in Canadian Arctic seawater

It is important to continue monitoring banned chemicals to establish trends and to be able to evaluate the effectiveness of national and international regulations. It is equally important to screen for and monitor new and emerging compounds of concern identified by the AMAP and the Canadian Chemical Management Plan. These compounds are priority pollutants and warrant further assessment and risk management if detected in the arctic environment since they meet one of the criteria for control, i.e. long range transport potential.

The main goals of the microplastics study was to quantify contamination and better understand sources and sinks, but it is important to continue this study to assess the need for long-term monitoring and ecological impacts. As a result of widespread contamination, a diverse array of wildlife is exposed to MPs.

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REFERENCES

Addison, R.F., Muir, D.C.G., Ikonomou, M.G., Harwood, L., Smith, T.G. 2009. Hexachlorocyclohexanes (HCH) in ringed seal *(Phoca hispida*) from Ulukhaktok (Holman), NT: trends from 1978 to 2006. Sci. Total Environ. 407: 5139-5146.

AMAP. 2017. AMAP Assessment 2016: Chemicals of Emerging Arctic Concern. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. 2017.

AMAP. AMAP Assessment 2011: Mercury in the Arctic. Arctic Monitoring and Assessment Program, Oslo, Norway, 2011.

Armitage, J.M., Schenker, U., Scheringer, M., Martin, J.W., MacLeod, M., Cousins, I.T. 2009. Environ. Sci. Technol. 43, 9274-9280 and 43, 1134-1140 and 43, 5830-5836.

Ballent, A., Corcoran, P.L., Madden, O., Helm, P.A., Longstaffe, F.J. 2016. Sources and sinks of microplastics in Canadian Lake Ontario nearshore, tributary and beach sediments. Mar. Pollut. Bull., 110: 383–395.

Becker, S., Halsall, C.J., Tych, W., Kallenborn, R., Schlabach, M., Mano, S. 2012. Changing sources and environmental factors reduce the rates of decline in the Arctic atmosphere. Atmos. Chem. Phys. 12: 4033-4044.

Bidleman, T.F., Kylin, H., Jantunen, L.M., Helm, P.A., Macdonald, R.W. 2007. Hexachlorocyclohexanes (HCHs) in the Canadian archipelago, 1. Spatial distribution and pathways of alpha-, beta-, and gamma-HCHs in surface waters. Environ. Sci. Technol. 41(8): 2688-2695.

Beattie, S.A., Armstrong, D., Chaulk, A., Comte, J., Gosselin, M, Wang, F. 2014. Total and methylated mercury in Arctic multiyear sea ice. Environ. Sci. Technol. 48: 5575-5582.

Buist, I.A., Dickins, D.F. 1987. Experimental spills of crude oil in pack ice. In International Oil Spill Conference (Vol. 1987, No. 1, pp. 373-381). American Petroleum Institute.

Burt, A., Wang, F., Pućko, M., Mundy, C.-.J, Gosselin, M., Philippe, B., et al. 2013. Mercury uptake within an ice algal community during the spring bloom in first-year Arctic sea ice. J. Geophys. Res. Oceans 118: doi:10.1002/jgrc.20380.

CACAR. 2013. Canadian Arctic Contaminants Assessment Report On Persistent Organic Pollutants – 2013. Muir, D., Kurt-Karakus, P. and Stow, J. (eds.). Northern Contaminants Program, Aboriginal Affairs and Northern Development Canada, Ottawa. xxiii + 487 pp + Annex.

Cai, M., Xie, A.,Möller, A., Yin, A.,Huang, P., Cai, M., Yang, H., Sturm, R.,He, J., Ebinghaus, R. 2012. Environ. Sci. Technol. 46 : 661-668.

Chaulk, A., Stern, G.A., Armstrong, D., Barber, D., Wang, F. 2011. Mercury distribution and transport across the ocean-sea-ice-atmosphere interface in the Arctic Ocean. Environ. Sci. Technol. 45: 1866-1872.

Dunton, K.H., Saupe, S.M., Golikov, A.N., Schell, D.M., Schonberg, S.V. 1989. Trophic relationships and isotopic gradients among arctic and subarctic marine fauna. Mar. Ecol. Prog. Ser. 56: 89-97.

Faksness, L.G., Brandvik, P.J., Sydnes, L.K. 2008. Composition of the water accommodated fractions as a function of exposure times and temperatures. Mar. Pollut. Bull. 56(10): 1746-1754.

Fingas, M.F., Hollebone, B. P 2003. Review of behaviour of oil in freezing environments. Mar. Pollut. Bull, 47: 333-340.

Foster, K.L., Stern, G.A., Carrie, J., Bailey, J.N.., Outridge, P.M., Sanei, H., Macdonald, R.W. 2015. Spatial, temporal, and source variations of hydrocarbons in marine sediments from Baffin Bay, Eastern Canadian Arctic. Sci Tot. Environ. 506–507: 430-443.

GESAMP. 2016. Sources, fate and effects of microplastics in the marine environment: part two of a global assessment. (Kershaw, P.J., and Rochman, C.M., eds). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No.94.

Glaeser, J.L., Vance, G.P. 1971. A Study of the Behavior of Oil Spills in the Arctic. United States Coast Guard Office of Research & Development, Applied Technology Division, Washington DC, 60 pp. Available online at http://www.dtic.mil/dtic/tr/fulltext/u2/717142.pdf.

Goni, M.A., O'Connor, A.E., Kuzyk, Z.Z., Yunker, M.B., Gobeil, Macdonald, R.W. 2013. Distribution and sources of organic matter in surface marine sediments across the North American Arctic margin. J. Geophys. Res: Oceans 118: 4017-4035.

Gouin, T., Wania, F. 2007. Time trends of arctic contamination in relation to emission history and chemical persistence and partitioning properties. Environ. Sci. Technol. 41: 5986-5992.

Hung, H., Bidleman, T., Breivik, K., Halsall, C., Harner, T., Holoubek, I., Jantunen, L., Kallenborn, R., Lammel, G., Li, Y-F., Ma, J., Meyer, T., Simonich, S., Su, Y., Sweetman, A., Weiss, P. HTAP 2010 Assessment Report Chapter C2: Observations and Capabilities. Edited by Sergey Dutchak and Andre Zuber. AIR POLLUTION STUDIES No. 19 EMEP/MSC-E. ISBN 978-92-1-117045-0.

Hung, H, Blanchard, P., Halsall, C.J., Bidleman, T.F., Stern, G.A., Fellin,P., Muir, D.C.G., Barrie, L.A., Jantunen, L.M., Helm, P.A., Ma, J., Konoplev, A. 2005. Temporal and spatial variabilities of atmospheric polychlorinated biphenyls (PCBs), organochlorine (OC) pesticides and polycyclic aromatic hydrocarbons (PAHs) in the Canadian Arctoc" results from a decade of monitoring. Sci. Total. Environ. 342(1-3): 119-144.

Kuzyk, Z.Z.A., Gobeil, C., Macdonald, R. W. 2013. Pb and 137 Cs in margin sediments of the Arctic Ocean: Controls on boundary scavenging. Global Biogeochem. Cyc. 27: 422–439.

Lohmann, R., Breivik, K., Dachs, J., Muir, D. 2007. Global fate of POPs: Current and future research directions. Environ. Pollut. 150: 150-165.

Lohmann, R., Muir, D.C.G., Zeng, E.Y., Bao, L.-J., Allan, I.J., Arinaitwe, K., Booij, K., Helm, P.A., Kaserzon, S.L., Mueller, J.F. 2017. Aquatic Global Passive Sampling (AQUA-GAPS) Revisited – First Steps towards a Network of Networks for Organic Contaminants in the Aquatic Environment. Environ. Sci. Technol. 51: 1060-1067.

Ma, J., Hung, H., Tian, C., Kallenborn, R. 2011. Revolatilization of persistent organic pollutants in the Arctic induced by climate change. Nat. Clim. Chang. 1: 255-260, DOI:10.1038/NCLIMATE1167.

Macdonald, R.W., Johannessen, S. C., Gobeil, C., Wright, C., Burd, B., van Roodselaar, A., Pedersen, T. F. 2008. Sediment redox tracers in Strait of Georgia sediments - can they inform us of the loadings of organic carbon from municipal wastewater? Mar. Environ. Res. 66 (SUPPL.): 87–100. doi:10.1016/j.marenvres.2008.08.001.

Meyer, T., Muir, D.C.G., Teixeria, C., Young, T., Wania, F. 2012. Deposition of brominated diphenyl ethers on the Devon Ice Cap. Environ. Sci. Technol. 46: 826-833.

Möller, A., Sturm, R., Xie, A., Cai, M., He, J., Ebinghaus, R. 2012. Organophosphorous flame retardants and plasticizers in airborne particles over the northern Pacific and Indian Ocean towards the polar regions: evidence for global occurrence. Environ Sci. Technol. 46: 3127-3134.

Panagopoulos et al., 2017, personal communication.

Neusitzer, T.D., Firoozy, N., Tiede, T.M., Desmond, D.S., Lemes, M.J.L., Stern, G.A., Rysgaard, S., Mojabi, P., Barber, D.G. 2018. Examining the impact of a crude oil spill on the permittivity profile and normalized radar cross-section of young sea ice. IEEE Geosci. Remote Sens. 56(2): 921-936. doi: 10.1109/TGRS.2017.2756843.

NORCOR Engineering and Research Ltd. 1975. The Interaction of Crude Oil with Arctic Sea Ice. Beaufort Sea Technical Report No. 27, Victoria, BC, 213 pp. Available online at http://www.dfo-mpo.gc.ca/Library/49602.pdf.

Rigét, F., Bignert, A., Braune, B., Stow, J., Wilson, S. 2010. Temporal trends of legacy POP's in arctic biota, an update. Sci. Total Environ. 408: 2874-2884.

Ryan, M.J., Stern, G.A., Kidd, K.A., Croft, M.V., Gewurtz, A., Diamond, M., Kinnear, L., Roach, P. 2013. Biotic interactions in temporal trends (1992-2010) of organochlorine contaminants in the aquatic food web of Lake Laberge, Yukon Territory. Sci. Total Environ. 443: 80-92.

Saupe, S.M., Schell, D.M., Griffiths, W.B. 1989. Carbon-isotope ratio gradients in western arctic zooplankton. Mar. Biol. 103: 427-432.

Stogiannidis, E, Laane, R. 2015. Source Characterization of Polycyclic Aromatic Hydrocarbons by Using Their Molecular Indices: An Overview of Possibilities. Rev. Environ. Contam. Toxicol., 234: 49-133.

Su, Y., Hung, H., Blanchard, P., Patton, G.W., Kallenborn, R., Konoplev, A., Fellin, P., Li, H., Geen, C., Stern, G., Rosenberg, B., Barrie, L.A. 2008. A Circumpolar Perspective of Atmospheric Organochlorine Pesticides (OCPs): Results from Six Arctic Monitoring Stations in 2000-2003. Atmos. Environ. 42: 4682–4698.

Sühring, R., Diamond, M.L., Scheringer, M., Wong, F., Pućko, M., Stern, G., Burt, A., Hung, H., Fellin, P., Li, H., Jantunen, L.M. 2016. Organophosphate esters in Canadian Arctic air: occurrence, levels and trends. Environ. Sci. Technol. 50: 7409-7415.

UENP. 2003. Regionally Based Assessment of Persistent Toxic Substances. United Nations Environment Program Chemicals, Geneva, Switzerland, 207 pp. Available online at https://www.researchgate.net/profile/Hindrik_Bouwman/publication/292286858_Regionally_based_assessment_of_persistent_toxic_substances_Global_reprt/links/56ac8fb408ae19a38513e2e7/Regionally-based-assessment-of-persistent-toxic-substances-Global-reprt.pdf.

Wang, F., Macdonald, R.W., Armstrong, D., Stern, G. 2012. Total and methylated mercury in the Beaufort Sea: The role of local and recent organic remineralization. Environ. Sci. Technol. 46: 11821-11828.

Wang, F., Macdonald R.W., Stern, G.A., Outridge, P.M. 2010. When noise becomes the signal: Chemical contamination of aquatic ecosystems under a changing climate. Mar. Pollut. Bull. 60: 1633-1635.

Wania F. 2007. A global mass balance analysis of the source of perfluorocarboxylic acids in the Arctic Ocean. Environ. Sci. Technol. 41: 4529-4535.

Wong, F., Jantunen, L.M., Papakyriakou, T., Staebler, R.M., Stern, G.A., Bidleman, T.F. 2012. Comparison of micrometeorological and two-film estimates of air-water gas exchange for alpha-hexachlorocyclohexane in the Canadian Archipelago. Environ. Sci. Pollut. Res. 19, 1908-1914.

Yunker, M.B., Macdonald, R.B., Vingarzan, R., Mitchell, R.H., Goyette, D., Sylvestre, S. 2002. PAHs in the Fraser River Basin: A critical appraisal of PAH ratios as indicators of PAH source and composition." Org. Geochem. 33(4): 489–515. doi:10.1016/S0146-6380(02)00002-5.

PUBLICATIONS

Firoozy, N., Neusitzer, T., Desmond, D., Tiede, T., Lemes, M., Landy, J., Stern, G., Mojabi, P., Rysgaard, S., Barber, D.G. 2017. An electromagnetic detection case study on crude oil injections in a young sea ice environment. IEEE Transactions on Geoscience and Remote Sensing, 55(8): 4465-4475, doi: 10.1109/TGRS.2017.2692734.

Gmelch, L., Hintelmann, H., Hickie, B., Kienberger, H., Stern, G., Rychlik, M. 2017. Risk-Benefit Assessment of Monomehtylmercury and Omega-3 Fatty acid Intake of Ringed Seal Consumption with Particular Emphasis on Vulnerable Populations in the Western Canadian Arctic. Frontiers in Nutrition, 4:30. Doi: 10.3389/fnut.2017.00030.

Godin, P., Macdonald, R.W., Kuzyk, Z.Z.A, Goni, M.A., Stern, G.A. 2017. Organic matter compositions if rivers draining into Hudson Bay: Present-day trends and potential as recorders of future climate change. Journal of Geophysical Research: Biogeosciences, 122 (AGU Publications). doi: 10.1002/2016JG003569.

Neusitzer, T.D., Firoozy, N., Tiede, T.M., Desmond, D.S., Lemes, M.J.L., Stern, G.A., Rysgaard, S., Mojabi, P., Barber, D.G. 2018. Examining the impact of a crude oil spill on the permittivity profile and normalized radar cross-section of young sea ice. IEEE Transactions on Geoscience and Remote Sensing 56(2): 921-936. DOI: 10.1109/TGRS.2017.2756843.

Pućko, M., Stern, G.A., Burt, A., Jantunen, L.M., Bidleman, T.F., Macdonald, R.W., Barber, D.G., Geilfus, N.-X., Rysgaard, S. 2017. Current Use Pesticide (CUP) and legacy Organochlorine Pesticide dynamics at the Ocean-Sea-ice-Atmosphere interface in Resolute Passage, Canadian Arctic, during winter-summer transition. Science of the Total Environment, 580:1460-1469, (Elsevier) doi: 10.1016/j.scitotenv.2016.12.122.

Geilfus N.-X., Pind M., Else B., Galley R.J., Miller L.A., Thomas H., Gosselin M., Rysgaard S., Wang F., and Papakyriakou T.N. 2018. Spatial and temporal variability of seawater pCO_2 within the Canadian Arctic Archipelago and Baffin Bay during the summer and autumn 2011. Continental Shelf Research (Elsevier) (accepted).

SECTION II. TERRESTRIAL SYSTEMS

Section II is composed of six ArcticNet research projects covering several biological and physical components of the Canadian Arctic terrestrial systems.

PERMAFROST RESEARCH FOR NORTHERN INFRASTRUCTURES AND IMPROVED COMMUNITY LIFE

Project Team

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ABSTRACT

This project is partly a continuation of ArcticNet's Project 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 select 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

- The coastal survey and classification of Nunavik's coastline has led to hazard risk analysis for regional marine infrastructures and Inuit communities.
- 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 the 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. Snow cover increases accordingly in new shrubs with warming impacts on permafrost.
- 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 in 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. Six more are under progress in Nunavik.
- Sustainable development of Arctic communities involves the expanding, researching and proving the methods to prolong the life of northern transportation and public 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 planned in support of the owner's strategic maintenance schedule.
- Our monitoring shows that the stability and safe operation of roads and runways built on permafrost are very sensible 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.
- Accordingly, a general calculation application was designed to determine optimal thickness of crushed rock or gravel embankments in order to preserve permafrost under infrastructures.
- A general numerical risk analysis approach for linear infrastructure on permafrost was designed and first applied to the Iqaluit airport. Sections of the runway more at risk were delineated. This risk analysis comes in support of financial risk analysis by the consortium who operates the airport under a 30 year contract with the governments.
- Avativut traning program: The program is expanding, particularly in the community of Kangiqsualujjuaq. After recent administrative changes, the Kativik School Board is considering using it again for training Inuit students in science. The Nunavut Climate change unit is also considering Avativut for its training and public information programs.
- PermaSim training software was used in Kugluktuk by the NIs as a teaching tool to Kugluk park staff, with great interest.
- Permafrost mapping and analysis of terrain changes were done for the communities of Jean-Marie River and Old Crow by the Yukon College (YC) members of the team.
- YC also runs a major program on mapping the sensitivity to permafrost thaw along the Dempster Highway with the Yukon Highway and Public Works Department. NIs from Laval are partnering.

- A new project to study permafrost conditions, ice-wedges and landslides was started in Kugluk Territorial Park with the park service of the GN and the community of Kugluktuk. Preliminary results already indicate that thawing of ice wedges has generated the formation of hundreds of small new ponds over the last decades. Inuit youth from the community participate actively to the project through summer student employment.
- Originally designed, customized, sensors to measure unfrozen water contents in permafrost were installed at a test site near Yellowknife and tests continue.
- A spinoff Company called LogR Systems was launched in 2017. It builds and sells a technically advance datalogger that has a great potential on the market, with accompanying I/O software. Small size, robust, large battery and memory capacity, multi-channel, competitive cost; all those qualities make it highly pertinent for the permafrost science and professional community.

RESEARCH OBJECTIVES

The original objectives of the project are:

- To map and improve knowledge of permafrost characteristics and temperature regime at local scales, i.e. at the scale of Arctic communities (1-2 km^2) to support the choice of foundation types for buildings of various sizes and functions and to assist in urban planning. Similarly, to characterize permafrost under existing transportation infrastructures that need to be adapted to face the impacts of climate change as well as for new infrastructure projects that shall arise such as roads, mine infrastructures, airfields and sea ports. In the course of the project, this objective was enlarged to also produce permafrost maps of regional scale as well as spatial and spatial analyses of land ecosystems evolving on permafrost.
- 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.
- To create a teaching tool and a computer-assisted course on permafrost for widespread Inuit and public use.
- To work in collaboration with ministries and industries 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 process to help selecting the best strategies for the construction and the maintenance of roads, airports and coastal infrastructures.
- To keep developing new methods for measurement and model-based predictions of permafrost terrain dynamics (i.e. ecological changes) and permafrost properties such as unfrozen water content, ice contents 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, and improved drilling techniques. As the measurement of temperature alone is of limited value for describing thawing permafrost, the development and use of such tools is a basis for future monitoring and early warning with respect to infrastructure integrity.

KNOWLEDGE MOBILIZATION

- ArcticNet Annual Scientific Meetings
- International and European permafrost conferences
- Regional workshops (ex. Yellowknife, NWT Earth Science symposium)
- Presentations and discussions in communities and schools.
- Invited talks in Government panels (Québec, Canada)
- Participation in decision-making committee (e.g. meeting on sustainable community development organized by KRG in Kuujjuaq in January 2018; Transport Canada network on infrastructures on permafrost, Iqaluit workshop on community permafrost mapping in March 2018)
- Contributing chapters to IRIS-4 second iteration (Housing, Coastal landscapes)

INTRODUCTION

Being soil or rock at temperatures permanently below 0°C 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 because soil particles and organic matter in permafrost are bonded together by ice under a variety of forms and origins; this creates a large number of "geocryological" facies that can be instrumental to interpret past geomorphological and climate-induced processes. 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 get 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 operational capacity. Indirect impacts in the public include decreasing quality of life and increasing health and safety risks. There is a need for better permafrost characterization to remediate to failing infrastructure and to build new ones. Some risk assessment processes are 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* brought 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 Northerners. 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 by supervised graduate students and their support staff. Projects are run 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

In the final year of the project, we further focused our work on addressing the demands and the needs of Inuit communities and territorial governments to increase both their knowledge on permafrost and their capacity to deal with permafrost-related issues, particularly for community land use planning. More support from permafrost scientists is also requested actually to 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. Still, the team's involvement in applied research for transportation infrastructure such as roads and airports was maintained on a high level. 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. On a more fundamental aspect, we kept making innovative contributions to permafrost science and engineering by developing and testing new measurements technologies in the field and in the laboratory and, also, by developing new approaches for networking data acquisition systems and for making data and knowledge publicly available.

ACTIVITIES

Progress in reaching the objectives in 2017-2018

Mapping of permafrost extent and properties, and measurements of thermal regime at all scales, in communities, and along coastlines

Mapping permafrost thaw and monitoring the thawing landscape in Jean Marie River First Nation territory, NWT

As the Jean Marie River First Nation (JMRFN), located 127 km southeast of Fort Simpson, had already completed a vulnerability assessment to impacts caused by climate change, the community had identified permafrost degradation due to a warming climate as a priority risk that required further investigation. An important step was for the NCE of Yukon College to produce a vulnerability map to permafrost thaw for part of JMRFN traditional territory. These surveys revealed that permafrost covers 51.5% (483.6 km^2) of the study area. Of the total area, 35.2% (170.22 km^2) has a high level of vulnerability and 15.9% (76.89 km^2) has a medium level of vulnerability. Patches of permafrost can be very large within areas of critical interest for the community. These large patches of permafrost represent areas that will become increasingly hazardous for travel; this is where most of the landscape changes are expected to occur. The changes in these large and vulnerable areas are likely to affect the wildlife that the community feeds on. Thawing of permafrost will alter large portions of wildlife habitat and wildlife diet and migration patterns are at risk to be affected. In response to this mapping result, the JMRFN wants to develop possible adaptation strategies to minimize the risks associated with these impacts. One of the first steps is to develop an adequate environmental monitoring program of the traditional lands to observe how changes are impacting JMRFN's lands. The nation's new monitoring program has two main objectives 1- to precisely document change in their landscape and orient choices for adaptation strategies, 2- to involve JMRFN youths in the preservation of their traditional lands, as well as promote their awareness in regard on the climate changes and their lands and way of life.

Mapping Permafrost Vulnerability in Vuntut Gwitchin Traditional Territory: Climate Change Impacts on Landscapes and Hydrology

In this new project, the Northern Climate ExChange (NCE), part of the Yukon Research Centre at Yukon College, will provide information about the sensitivity of key areas within the traditional territory of VGFN to permafrost thaw and related hydrological changes. The first aim of the project is to produce a permafrost vulnerability map that can be used by the community to identify activities and culturally important sites that may be impacted by landscape change and permafrost thaw. Access to the land and traditional activities bring important economic, health and cultural benefits for VGFN members and they are concerned that landscape change will impact their ability to access traditional foods and engage in the traditional economy. The project will provide VGFN with information, including a geospatial database and maps, that will enhance their resiliency as climate and landscape changes continue. At the same time, the project will increase our understanding of the interplay between permafrost and hydrology in the Old Crow Flats and update the permafrost monitoring network in the area. The project will also pilot a methodology that can be used in other northern Canadian regions to map permafrost vulnerability.

Specific objectives are to:

- Compile a baseline geospatial database focusing on permafrost conditions such as substrate nature, ground temperature, and excess ground ice, as well as other factors such as active-layer depth, hydrological connectivity, and recent changes in vegetation cover;
- Monitor seasonal and inter-annual lake hydrological conditions and investigate relationships with surrounding land cover and permafrost conditions;
- Prepare thematic maps including one that ranks sensitivity of terrain units to permafrost thaw based on multiple factors. Those maps will be used by the community to determine which activities and culturally important sites may be impacted by landscape change;
- Contribute to community capacity-building by developing a permafrost and water community-monitoring program with VGFN.

This two-year project will rely on an interdisciplinary approach bridging various methods of environmental science ranging from remote-sensing work that will be done as part of the ABoVE program to permafrost and environmental assessment involving core sampling and permafrost temperature monitoring. The proposed fieldwork and community-monitoring program will be coordinated with other research programs in the Old Crow Flats, including the proposed Polar Knowledge Canada project *Checking the bank account: community-driven monitoring of the health, population dynamics, predation, and habitat of Canada's Arctic muskrats*. NASA's ABoVE affiliate Dr. Kevin Turner has secured tasking of several leading-edge remote-sensing products during 2017. The total methodology includes the following steps:

1. Development of a working group of community members and project team members;
2. A workshop with the community and research team to identify priority areas of interest within Old Crow Flats and locations where landscape changes have occurred;
3. Integration of information gathered during the workshop within a geographic information system (GIS) database with other data such as surficial geology, geomorphologic features, geocryological observations, remote sensing and aerial imagery, etc. The GIS data base will be used to orient field investigations and select specific study areas;
4. Field investigations to collect information such as soil texture, organic layer thickness, active layer thickness, cryostratigraphy, ground ice content, ground temperature, lake water level and water isotope tracer monitoring;
5. Data analysis and characterization of the study area will produce thematic maps representing investigated properties;
6. Creation of a permafrost vulnerability map, featuring three levels of vulnerability: low, moderate, and high, as well as associated land cover and hydrological information;
7. Concurrently to steps 1-5, a community permafrost and hydrological monitoring system will be developed and installed with VGG and VGFN elders and youth in Old Crow Flats, at a site that is culturally significant to the community, and in Old Crow;
8. A community meeting to present the permafrost vulnerability maps, data from the field program, data and information on the community-monitoring program, and information on landscape processes and anticipated changes in the area;
9. Produce project report and other deliverables for VGFN, POLAR and other end-users; and
10. GIS training workshop for VGG staff, including how to use project deliverables in land and natural resources management processes.

2017 Research Activities

Permafrost research was attempted twice in the Old Crow Flats and was unsuccessful due to weather and a lack of helicopter fuel availability after a summer of intense forest fires. We have adjusted our fieldwork plans for Year 2 to accommodate more field sites to make up for changes to Year 1 fieldwork. Project partners conducted field research on water, water quality, and water/permafrost interactions during the summer field season.

Mapping snow cover, vegetation and active layer variations at the Bylot Island research station

Current changes in high arctic tundra are driven by large scale climatic variables but locally controlled by microclimatic factors where the buffering effect of vegetation, organic layer and snow cover can lead to contrasting conditions (e.g. wetting or drainage, thermokarst or shrubification). We are studying the interplay between landscape hydrology and vegetation along a topographic gradient at Bylot Island, Nunavut (Figure 1a). We collected high-resolution images were collected with a UAV (unmanned aerial vehicle) at the end of winter and in midsummer 2017 to develop snow thickness maps (MSc Loyer). The images were georeferenced with targets placed on the surface and located with a GNSS (precision <2 cm). Photogrammetric analyses yielded high-resolution DEMs of the snow surface (May) and snow-free surfaces (July) (e.g. Figure 1b). DEM differencing will provide snow thickness maps (in progress) that will be validated with manual snow depth measurements conducted along two transects. In May 2017, snow depth reached up to 1.2 m along the transects with a median around 30-35 cm. Preliminary results from snow height maps revealed snow accumulations up to several meters in thermokarst ravines and some polygon troughs. Vegetation structure was characterized and related to NDVI values of a high resolution (2 m) 2016 Pleiades satellite image of the same sector (BSc Vallerand) where surface microclimate, moisture and active layer depth continued to be monitored (2nd season, BSc Roy).

Microtopography in the form of earth hummocks and polygons can cause differences in snow accumulation and melting over short distances (<1 m) that are reflected in ground surface temperature and vegetation. In order to assess the long-term climate sensitivity of the snow cover and coupled soil thermal and moisture regimes in this tundra system, PhD Khani will simulate the conditions with a physically based-model using forcing and validating data available from the on-site SILA station (snow surveys, ground temperature and moisture) in combination with our spatially distributed dataset.

In addition, Maxime Tremblay completed his MSc thesis on the erect shrub *Salix richardsonii* and in collaboration with ecosystem ecologist Vincent Maire we continued the analysis of soil carbon from cores collected under dense erect shrub patches and in adjacent shrub free patches. In addition to strong differences in active layer depth (60 cm vs 30 cm, with and without erect shrubs, respectively), the storage and mineralisation of the young and old carbon of the soil appear to be differentially affected by the presence of shrubs and the fertilisation effect of sediment deposition. The factors promoting the growth of erect shrubs at this northern limit of distribution will be further studied in 2018. We plan to use UAV flights in summer to evaluate erect shrub distribution in the valley.

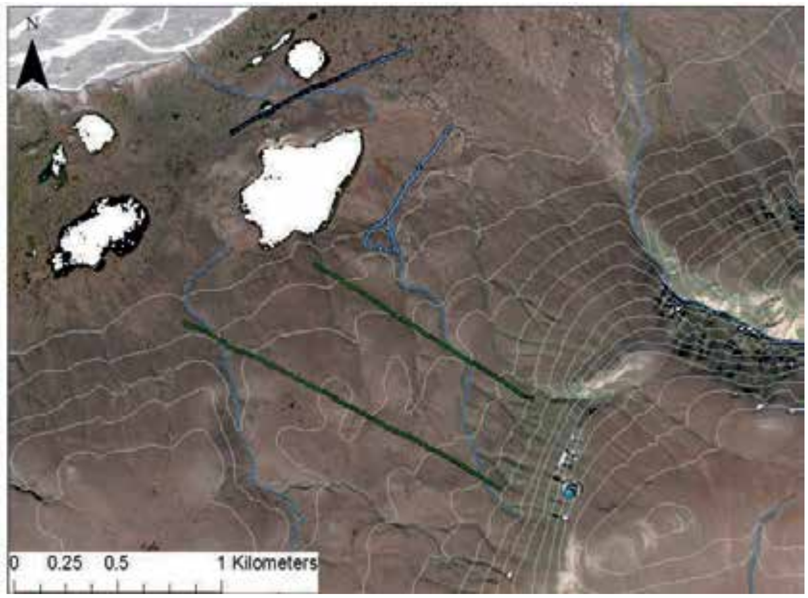
Mapping and assessing the impacts of tundra shrubification on permafrost terrain in the Low Arctic and the Sub-Arctic

Efforts to quantify the impact of shrubification on northern ecosystems continued near treeline at Umiujaq (Nunavik) where we added decomposition bags to our study sites under varying shrub cover and fertilisation regime (BSc Joannie Vertefeuille). Boudreau and Lévesque obtained a research contract with Ministère des Forêts de la Faune et des Parcs (MFFP) du Québec aiming to propose scenarios of vegetation productivity and structural change in Northern Québec for 2100. This research stems in part from the knowledge gained through ArcticNet supported projects on shrub dynamics (e.g. Paradis et al. 2016, Pelletier et al. (in review), Lemay et al. 2018) and will build on regional climate models and permafrost mapping efforts (L'Hérault et al., 2017). Currently, available data are being assembled (including topographical, permafrost and satellite information) and will be analysed to quantify the abundance and distribution of vegetation types from treeline to herb tundra. Scenarios produced will support further studies on wildlife distribution and will provide provincial and regional end-users with a comprehensive knowledge of the potential for change in structure and productivity of these northern ecosystems.

Assessing the impact of 25 years of climate warming on active layer and ice wedge dynamics in Narsajuaq near Salluit, Nunavik

Again in 2017, 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, the year of field work for a previous Ph. D. thesis on ice wedges in permafrost. Using technologies such as analysis and mapping on a high-resolution satellite image of July 2017, a new automated meteorological station, thermistor cables, snow cover sensor and revisiting field survey sites of 1990-1991 now allow report on 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 1993, the climate has warmed by 3 °C!

The active layer increased by more than 200% (from about 25 cm to 60 cm in organic-rich soils) and the top of the ice-wedges thawed in consequence.



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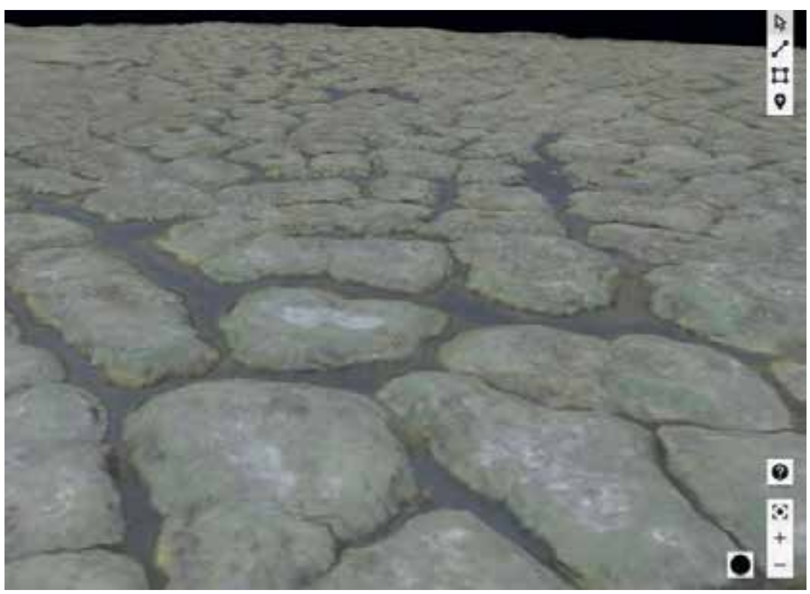

B

Figure 1. (a) Map of study area in Qarlikturvik valley on Bylot Island, Nunavut, showing the snow depth transects and the position of the time-lapse camera; (b) example of derived 3D orthophoto (July 2017).

What is actually thawing are the up-growth forms of ice wedges that had formed in the period 1948-1991 under a cooling climate regime. Most main, or "mother" wedges at greater depth are still intact deeper in the ground. Tunnels are left in the active layer where some ice wedge tops were present, allowing subsurface flow for air and water in conduits (Figure 2, a to d). Vegetation surveys in August 2016 and 2017 indicate that mosses and peatlands have expanded and gotten somewhat thicker during the 27-year interval over the low center polygons and in furrows over ice wedges, therefore likely slowing the warming of the ground by providing some surface insulation. Concurrently, over 100 pits were sampled for soil carbon contents and to validate the making of a high-resolution soil-carbon map. We found that landforms such as former lake beds and former river channels on fluvial terraces have thicker organic and alluvial accumulations and some syngenetic permafrost that has higher carbon contents that dry terrace surfaces. Ground temperature and climate records will be retrieved in August 2018 from the automated station.

The overall aim of this project is to understand the interplay of all the components of the changing system with their influence on the ground temperature regime and the thermo-dynamic equilibrium of permafrost.

The community of Salluit manifests great interest in the study and its outcomes and is very supportive of the field team.

Mapping landslides and ice-wedge networks in Kugluk territorial park, Nunavut

This new project was started in June 2017 at the request of the Government of Nunavut and the community of Kugluktuk. The ATV trails to access in the park (Bloody Falls) have a history of permafrost disturbances. The sections of the tracks that run along the bluff edges along the Coppermine River are themselves being eroded by retreating head scarps of active landslides in thick deltaic sand deposits. The aims of the project are:

- To assess the sensitivity of permafrost to disturbance by vehicle tracks and to help designing and routing a new permanent track across the park that will allow community members to reach hunting grounds beyond the park area and, also, ease tourists' access within the park.
- To analyse how climate warming and thawing of the permafrost (thickening of the active layer) is affecting the landscape and can possibly make the problem more difficult to solve.
- To measure the rate of recess of landslide head scarps and better understand the detailed processes of cliff face thawing and gully erosion and the role ice wedge decay around landslides plays in destructing slopes.
- To help park management people and a group of young Inuit to acquire basic knowledge on permafrost thermal regime, landforms and ice contents through a practical involvement in field work and special course sessions.
- To study permafrost with high resolution surveys along the projected route of the new ATV trail and help its design.

The project is done in collaboration with Polar Knowledge Canada scientists from the not far away Cambridge Bay research station. Field work was done in July 2017. A thermistor cable with datalogger was installed in a drill hole. Bench marks were set along head scarps to measure cliff retreat rates. Comparisons and mapping from air photographs of 1954, 1993 and 2017 reveal that the terrain generally got wetter and that hundreds of new small ponds were created along the dense network of ice wedges (Table 1 and Figure 3). This is likely due to thaw at the top of permafrost induced by climate warming, as reported Arctic wide in the international literature. A reporting and training session was held in Kugluktuk on February 15, 2018.

In 2018, two more thermistor cables will be installed to measure differences in ground thermal regime between flat land and depressed, snow-filled, eroded ice-wedge furrows in the polygonal terrain. A 3 km long high resolution GPR profile will be run along the projected ATV trail to detect all ice wedges and measure their size along the route; this shall help design the sensitive crossings along the trail.

Nunavik coastal mapping and classification

Classification of the coastline of Nunavik into segments was continued from the video and photographic data acquired by helicopter flights in 2016 and 2017

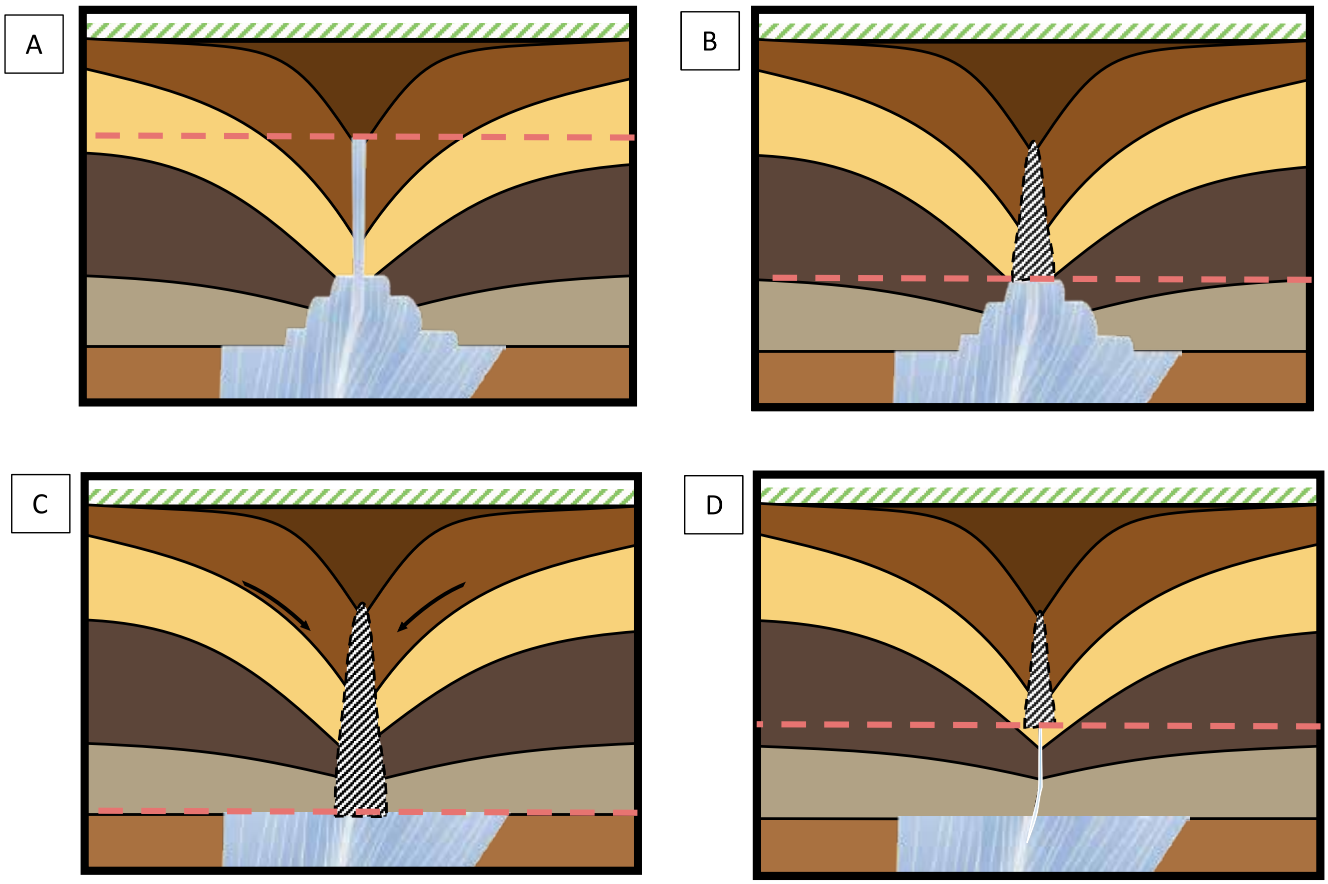

Figure 2. Melting sequence of an ice wedge with upgrowth forms. Over the course of the second half of the 20th century, the ice wedges in the Narsajuaq river valley were rejuvenated and upgrowth forms grew (a). Because of climate warming, the active layer has deepened and the upgrowth forms have melted, creating underground tunnels above the wedges (b). The tunnels eventually collapse from below because deeper mineral soil layers are not as cohesive as top organic layers and deeper layers are subject to more pressure (c). Due to a recent cooling trend in Nunavik, the active layer moved up and temperatures were cold enough to induce soil cracking and create ice veins (d).

(A. Boisson's Ph.D. thesis). One international conference paper featuring the dominant landforms and processes alomg the Nunavik coastline is now accepted for publication (Boisson and Allard, in press). Landforms and processes deemed unique to the emergent coasts of Nunavik were identified and will make the subject of thesis chapters/scientific papers. One paper concerns the formation of very intricate coastal patterns of islets, bays, spits, beaches, tidal marshes, flats, lagoons as the submerged glacial landforms (DeGeer moraines, drumlinoids, eskers) are emerging from the sea floor with the on-going post-glacial uplift and reworked by waves and sea ice. When they finally become terrestrial with uplift, those new coastal features further evolve into a mosaic of land ecosystems. Permafrost invades those ecosystems. One key region formed by those processes in the Kovic Bay region which is a major cultural and resource area jointly exploited by the communities of Akulvik, Ivujivik and Salluit. Raised lagoons and lakes retained by dams formed by high-tide boulder barricades in the macrotidal environment of Ungava Bay are also geomorphological features so far undocumented in the literature. Finally, we mapped the new permafrost features such as frost cracks, new polygons and heaved mounds in permafrost that is currently aggrading in emerging and recently emerged sediments. As the newly emerged land gets exposed to climate, permafrost can form; this is a rare place in the World where this is occurring. Figures 4 and 5 show the aggradation of new permafrost as measured by a thermistor cable set at sea level in lagoon sediments on the east coast of Hudson Bay. Three papers are in preparation.

The databank of video (10000 km) and high-resolution photographs (n > 37000) of the coastline is publicly available and is now used by the Kativik Regional Government to assess coastal submersion/erosion risks in communities. The Québec Ministry of Transports also ordered a study of risk assessment for the port facilities in villages based on the coastal survey.

Permafrost knowledge transfer and technical support to Inuit communities

Our project of improving maps of surficial geology, permafrost conditions and construction potential for Nunavik communities was continued in 2017 with funding from Ministère des Affaires Municipales et de l'Occupation du Territoire du Québec. Five communities where visited in July 2018: Kangiqsualujjuaq, Tasiujaq, Kangiqsujjuaq, Inukjuak and Umiujaq. More drill holes were made to improve the resolution of permafrost characterization to fit the scale of the villages and better meet knowledge needs of geotechnical conditions for housing programs. One hundred and one ground penetrating radar survey lines totalling over 30 km were run in less known parts of the municipalities with the intent particularly to detect shallow bedrock under the Quaternary sediments. This information is becoming essential to select stable construction terrain, particularly by driving and anchoring piles at shallow depths, hence at lower cost eventually. Some key results are:

- Kangiqsualujjuaq: a still non-built sector in the center of the community has a thick sandy soil deposit with very little ice content. It offers potential for installing new buildings. The tills on the the valley side are also ice-poor; with improved surficial drainage they can be built on.
- Tasiujaq: the permafrost is very stony and ice contents are spatially very variable and practically unpredictable. But the municipality has plenty of fill material to build pads for housing and an area of rock outcrop adjacent to the village is still unbuilt.
- Kangiqsujjuaq: an unbuilt area with shallow bedrock under sand was mapped adjacent to the community, thus offering excellent potential. But a sloping sector sensible to surface flooding and potential thermo-erosion was also delineated in another sector near the community, to be avoided.
- Inukjuak: at the request of the community, most of the field work was concentrated on the east bank of the Innuksuak River where they hope to re-occupy and urbanize an historical living area. The surveys delineated rock and shallow bedrock areas suitable for construction.

Table 1. Number of lakes and ponds (n), total area in water (Tot. sup.), mean, minimun, maximum size of water bodies mapped from air photos and satellite images in 1954, 1993, 2010. The number of small and very small lakes was multiplied sixfold from 1954 to 2010, for a wetter tundra.

Year	*n*	Tot. sup. (m^2)	Mean (m^2)	Min (m^2)	Max (m^2)	Std. dev.
1954	244	362754,0	1486,7	8,6	37596,9	4320,1
1993	618	386572,1	625,5	1,4	41607,7	2860,7
2010	1413	446442,5	316,0	0,9	44104,7	2072,8

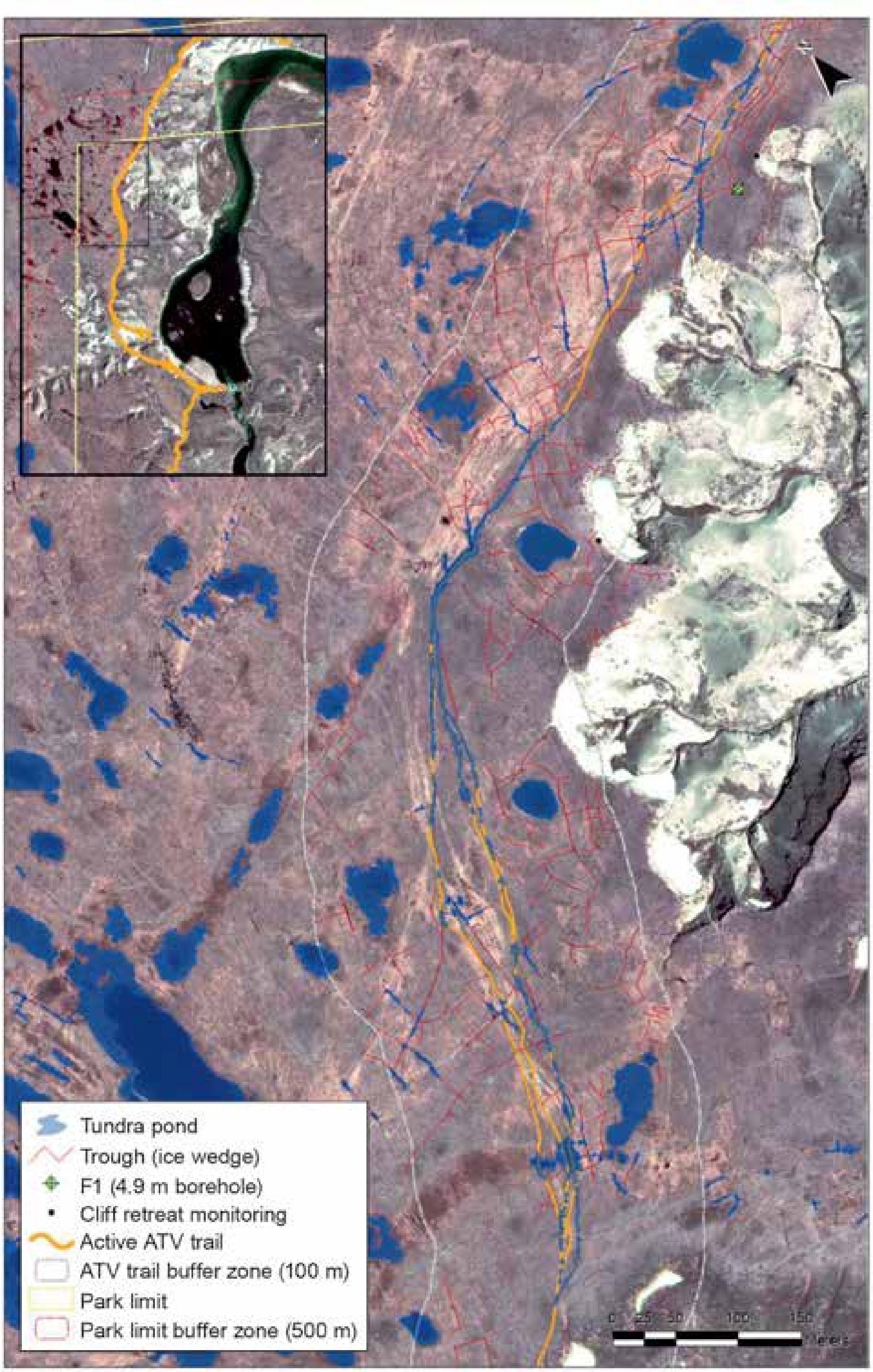

Figure 3. Map of ice-wedge polygons and landslides along the ATV route corridor in Kugluk territorial park, along the Coppermine River, near Kugluktuk. Background satellite image dates from 2010. Note the abundant water bodies, many of them over ice wedges.

- Umiujaq: a so far poorly studied sector south of the actual village and deemed unsuitable at first glance in fact offers solid ground conditions for opening a large new division for the community. (Figure 6).

In addition, ground temperature monitoring instrumentation using a new model of datalogger (documented later in this chapter) was installed at existing previously hand-read thermistor cable sites and at new ones in Kangiqsualujjuaq, Kuujuaq and Salluit. In Salluit, the CEN's SILA meteo station in the community was also upgraded. This new data acquisition capacity will be useful to analyse ground temperature conditions in the communities and help calibrate models of permafrost temperature change for the coming decades. This new action will be in support of terrain selection and decision-making for land use management. This predictive modeling over improved local permafrost conditions will constitute phase 2 of this project, starting in 2018 and ending in 2020.

Development of teaching tools for Inuit and other stakeholders

The general teaching tool developed by the team over the three-year project is the Permafrost Learning and Evaluation Situation (LES) in Avativut. In summary:

- The English translation of all educational material designed for the Permafrost LES was completed by the Kativik School Board.
- Allard's team used and adapted some Avativut educational material from the Permafrost LES, for its permafrost training sessions. For instance, the software PermaSim was used as a taching tool in

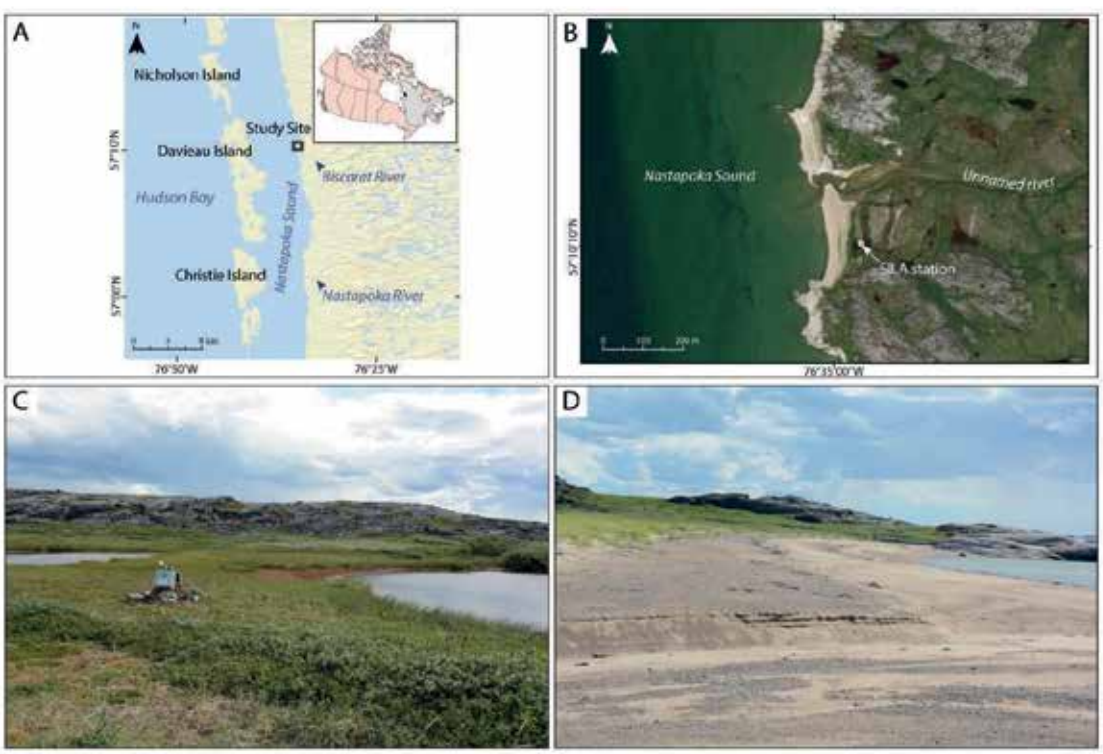

Figure 4. A) Location of the Biscarat site, B) air photo of the site and location of the thermistor cable behind a beach ridge, C) the data recording instrumentation, D) the beach front near the side.

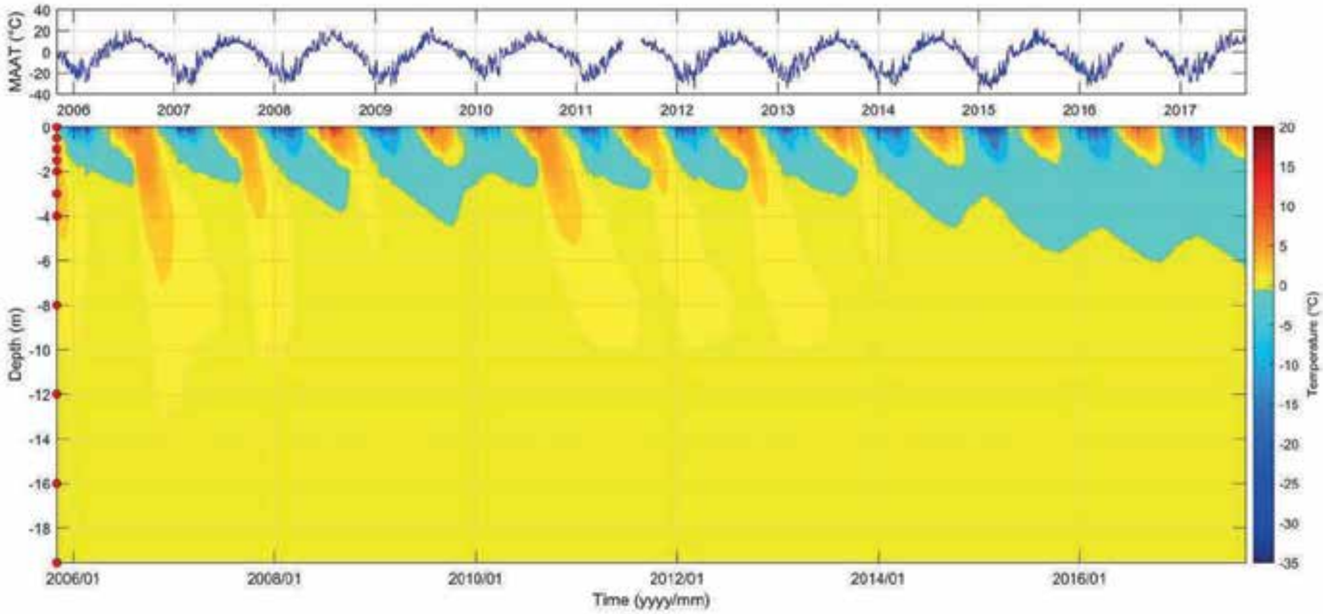

Figure 5. Time-graph of ground temperature at the Biscarat site (0-20 m deep). Starting in 2014, permafrost has begun to form in the emerging coastal sediments, now reaching 6 m in thickness.

the Kugluktuk project. In Nunavut, the material prompted interest in the educational activities initiated by the team in other regions, particularly in Nunavik.

- Major changes are actually going on at the Kativik School Board, including an inuitization process leading to a change in its name, now Kativik Ilisarniliriniq (KI), and the revision of all the curriculum.
- The KSB Math, Science and Technology curriculum was at the heart of a debate between the Quebec Ministry of Education and the Kativik School Board regarding the recognition of a high school diploma rather than a simple attestation, which was the case until July 2017. This situation was preventing some students to access post-secondary programs. All these factors have impacted the evolution and implementation of the Avativut Program:
  - » On May 17, 2017, the Minister of Education appointed a senior staff to work with the school board on programs accreditation, as well as ongoing technical and pedagogical developments. On July 12, 2017, the Ministry of Education approved the progression of learning of the school board's Secondary IV Mathematics and Sciences and Technology programs. As a result, when completing these courses, Nunavik students will now receive the mandatory credits leading to a Secondary School Diploma. https://www.kativik.qc.ca/diplomas-issued-students-received-attestations/.
  - » The KSB is also working on some new initiatives such as Inuit-centred environmental sciences for secondary students, a land-based curriculum, some career and community development courses, as well as completing the framework for full integration of the first and second languages curriculum, which is already in progress. Nunatsiaq News June 28, 2017. http://www.nunatsiaqonline.ca/stories/article/65674nunavik_makes_progress_on_diploma_issue_curriculum_development/.

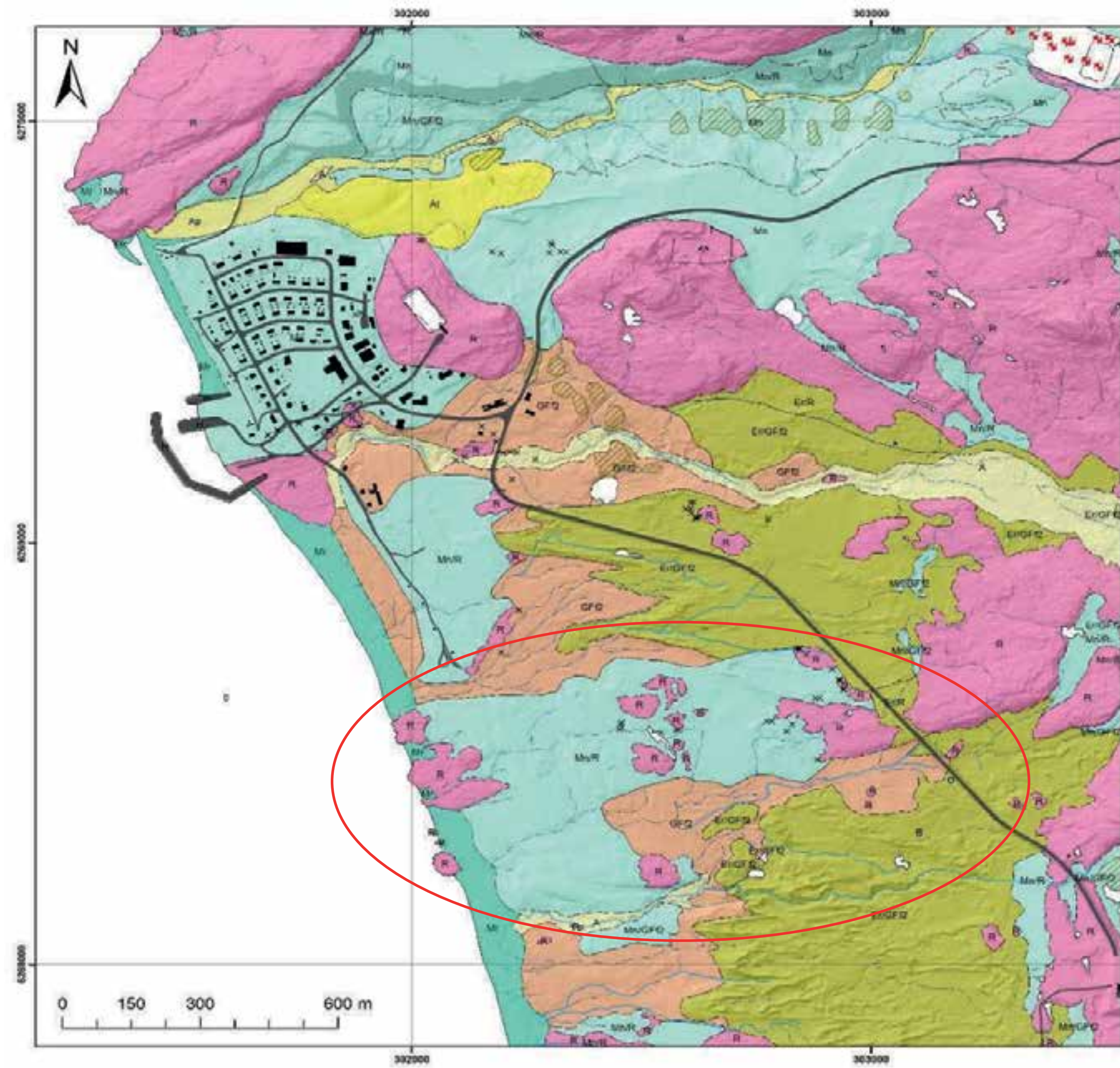

Figure 6. Revised surficial geology map of Umiujaq. Red ellipses circle areas were changed from the first version. Purple areas are bedrock. In area c the blue area is thin beach sand over bedrock.

- Due to a high staff turnover and the departure of some of our key contacts at Kativik Ilisarniliriniq (KI), there was a misperception of students collecting data for researchers' interest only. The Avativut Team managed to meet with Ms. Yasmine Charara, Research and New Paths Manager at KI, in Quebec City on December 2017.This meeting reopened the discussion and allowed to inform her on the creation of the Avativut Program partnership with KSB.

Support of infrastructure renovation and construction

Development of a Climate-Resilient Functional Plan for the Dempster Highway

This new project started in 2017 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 Yukon 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 being carried out by the Northern Climate ExChange, part of the Yukon Research Centre at Yukon College and a consultant (associate Engineering) 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 longterm 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 is:

- Taking climate change impacts into account directly: 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.
- Merging findings from multiple studies and conducting new research at key locations: This project will improve fundamental knowledge and understanding of climate change impacts in the region. This has potential for broad application in other subject areas including the installation of north optical fibre line, the development and maintenance of other new or existing linear infrastructure, and potentially in the management of wildlife in the region more broadly.
- Linking directly into the functional planning process: We are ensuring that the future costs associated with the maintenance of transportation infrastructure takes potential climate change impacts into account.
- Merging vulnerability assessment and planning into a more holistic and cost effective single project.

2017/2018 Activities

Field investigation: Following pre-field-work visit and field investigations carried in 2016, the second round of field investigation occurred in June and July 2016, and consisted in ERT surveying, borehole coring, ground temperature monitoring, and ground penetrating radar (GPR) investigation led in collaboration with Pr. Michel Allard, Laval University. Additional 200 m-long ERT surveys were made at km 375, km 421, km 424, km 438, km 442, km 447, km 454, and km 458. For each site, two type 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. GPR investigations were made at km 95, km 102, km 116, km 124, km 126, and km 192. Geotechnical borehole were made at km 95, km 116, km 126, km 375, km 424, km 442, km 447, km 454, and km 458; all sites except one (km 447) were instrumented for ground temperature monitoring. Ground temperature data were downloaded during a road trip on the Dempster Highway in September 2017.

Laboratory and desktop analyses: Results of the ERT surveys were post-treated and analyzed at the NCE using inversion software (Res2DInv 64 and Res3DInv 32). Laboratory analyses were carried out on permafrost cores to measure the properties of the permafrost samples. Both soil grain characteristics and ice characteristics were evaluated. To evaluate soil grain characteristics, 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 were quantified. Ground temperature data were plotted and analysed.

Reporting: The results of the survey was presented to HPW and Associated Engineering in a report (Calmels et al. 2018. Summary of Climate- and Geohazard-related Vulnerabilities for the Dempster Highway Corridor, 216p). Integration of the result and final reporting of the project will be carried on by Associated Engineering by March 2018.

ERT and Temperature Monitoring to Assess the Effectiveness of Insulating Culverts

The movement of surface water across linear infrastructures (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 lifespan. 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 have been attributed to 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 beneath the culvert through temperature monitoring.

Results of the study will allow HPW to monitor permafrost condition under the culvert using a non-invasive and cost-effective approach that can be replicated elsewhere in 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.

Project activities

The activities for this project include:

- General 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 layer buried under the culvert, and also temperature sensors buried above the insulation.
- Data retrieval from the site of the culvert and analysis of the data.
- Preparation of a report that documents the installation of the above-noted sensors, interprets the impact, if any, of the insulation layer below the culvert, and describes a protocol for data collection. Recommendations for replicating this study in other locations will be part of this report.

2017 Activities

- June 2017: Figure 7 presents the design of the km 381 culvert monitoring setup. Data were collected form the loggers connected to the 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. An ERT survey was performed using a Wenner and dipole-dipole arrays, by connecting the ERT system to the 24-electrode ERT monitoring array located below the insulating layer. Data were downloaded from the 5.55 m deep borehole drilled in the field, facing the culvert, on the right-hand side.
- November 2017: All data collected to date were analysed and presented to a workshop of the Transport Canada's Northern Transportation Adaptation Initiative (NTAI), at Edmonton, AB, November 27 &28, 2017.
- February — March 2018: Development of draft technical report, and final production of Technical report.

Development of a risk analysis tool for managing and developing transportation infrastructure on permafrost

The goal of this project was to create tools for the management and design of existing and new infrastructure in permafrost regions.

During the course of the project, a review of the literature was conducted to determine the state-of-knowledge with regards to the use of quantitative risk analysis in geotechnical and permafrost engineering, the dangers to permafrost transportation infrastructure, and available statistical methods and data for permafrost soils. No quantitative risk analysis studies had been reported within the literature reviewed; however, qualitative risk assessments had been completed for permafrost transportation infrastructure. The embankment-supported permafrost infrastructure dangers identified for inclusion within the tool encompass the structural and gradient failure of culverts, total and differential thaw settlement, particle bridging (via soil particle position), and active layer detachment landslides. The possible mechanisms for soil bridging over cavities made by thawing ice masses belowground were reviewed; particle bridging, unsaturated soil mechanics and frozen soil flexure were determined to be reasonable theoretical bridging mechanisms; a journal article is under peer-review. While data on the variability in geotechnical properties of unfrozen soils is regularly mentioned, no comprehensive review of permafrost property variation was found in the literature. A paper discussing the variability of permafrost geotechnical index properties, as derived from Geological Survey of Canada databases, is currently in press in Cold Regions Science and Technology.

An Excel macro-based computer program has been developed using Monte Carlo Simulation analysis methods and common permafrost analysis equations for thermal and mechanical stability. A Monte Carlo Simulation starts by selecting a value for each random variable, from a probability density function, within an analysis and uses those values to calculate the outcomes of all the selected equations. Repeated simulations, between 1,000 and 10,000 for this project, are then used to determine hazard. In this program, the random variables include climate (air thawing index, thaw season duration), permafrost (n-factor, permafrost temperature) and geotechnical properties (idealized soil profile with total and unfrozen moisture content, dry density and specific gravity). The user inputted information and danger limits are used with the equations to calculate current hazards. Thaw depth is determined using the Modified Berggren equation with its associated settlement from empirical thaw strain equations reported in the literature.

Since changing climatic conditions heavily impact permafrost infrastructures, an assessment of the future hazards is required to plan for an infrastructure's future. This was completed via a fragility assessment analysis by varying Mean Annual Air Temperature, and recalculating climate parameters and hazards. Consequences are calculated via direct costs (engineering design, material, labor and equipment costs) with applied factors (subjective scalar factors) for social and casualty impacts from a danger's occurrence. The goals, mathematical danger descriptions, and organization of the computer program were presented at ASCE's 1st Congress on Technical Advancement in September 2017 via an oral presentation and conference paper.

The analysis method and tool were applied to the Iqaluit Airport site in 2017 to determine settlement and particle bridging risk. The geotechnical, climate and permafrost data were determined from boreholes and laboratory tests of soil samples for each geologic setting, reported climate conditions, and thermistor strings from the Iqaluit airport project herein reported. Danger limits were calculated based on data from the reconstruction project agreement. The direct costs were determined from earned value reports of the airport's recent reconstruction. The indirect factors were based on citizen and business owner interviews and the judgment of the author.

The highest risk occurred for thaw settlement within the fine-grained, ice-rich, glaciomarine and lacustrine geologic settings of the airport followed by particle bridging. A fragility assessment included reanalyzing hazard based on site warming of 2.5°C from 2010-2050. The cumulative average thaw settlement through time was used to determine repair and reconstruction cycles. Present value analyses of the glaciomarine geologic setting confirmed the financial efficacy for the addition of insulation to the embankment section over

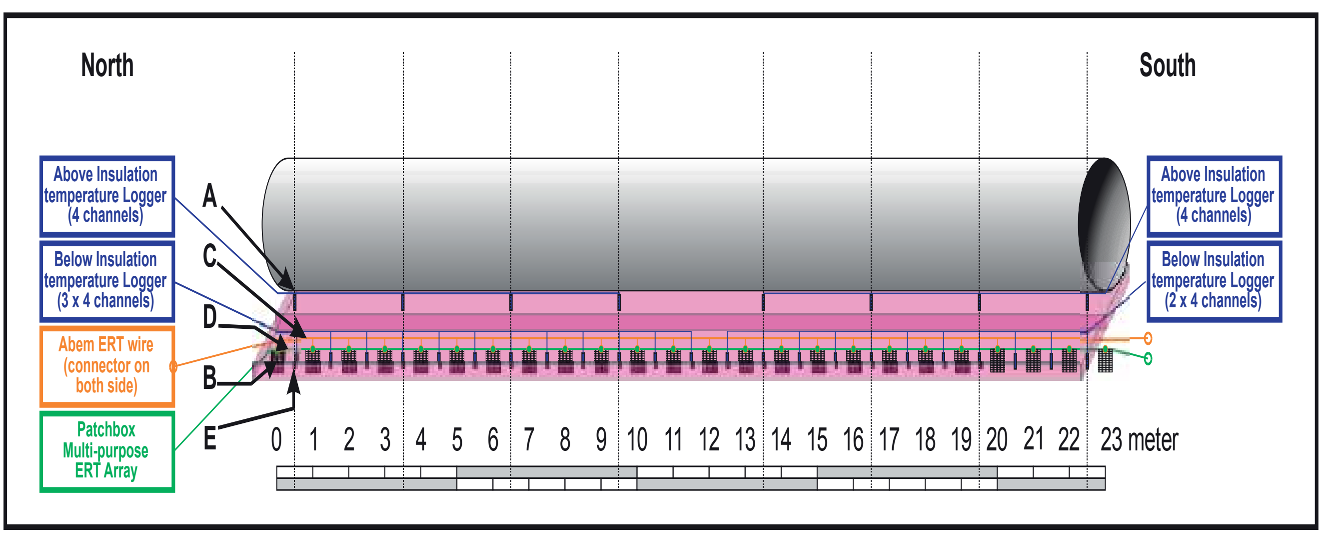

Figure 7. Design of the km 381 culvert monitoring setup.

ice wedges. While this program has only been applied at one site to date, this analysis can be carried out elsewhere and for any type of permafrost-supported linear infrastructure.

Development of design tools for convective mitigation techniques to preserve permafrost under transportation infrastructures

The objective of this project is to develop a rationale procedure for the thermal design of embankment on permafrost.

The heat balance-based method, which calculates the net flux at the in-situ-soil/embankment interface, should allow the assessment of long-term embankment thermal stability considering the effects of climate change. In case of unstable embankment, the method will allow to determine the amount of heat to be extracted, which will support the selection and the design of heat extraction methods. The project focused initially on the use of air convection embankments (ACE) for heat extraction and thermal stabilization of unstable embankments.

A 2D thermal conduction model was developed with SVOffice 5 Suites, considering ice-water phase change. The model was calibrated with field data from the Beaver Creek test site in Yukon. Site-specific parameters, such as soil properties, near surface air temperature, and embankment dimension were used as input parameters. Based on site conditions and embankment thickness, the calculation of heat balance at the soil/embankment interface allows the assessment of thermal stability of the embankment.

The model was used to develop a design chart (Figure 8), to estimate heat balance at the soil/embankment interface. The chart allows for a quick assessment of the critical yearly average thermal gradient corresponding to zero heat balance for varied embankment thicknesses. Above the critical thermal gradient, the heat balance is positive (heat accumulation) and, the embankment is thermally unstable, so permafrost degradation is likely to occur. If permafrost is thermally stable, at or below the critical thermal gradient, the effects of climate warming can be added into the analysis to predict when the embankment will become thermally unstable.

Open-graded aggregates are used to facilitate air flow in ACE. This technique extracts effectively heat from embankment during winter due to the difference of air density in the pore space due to the temperature variation between the surface and the inner embankment causing natural convection. A coupled heat conduction and convection 2D thermal model was developed, using the heat balance approach, to investigate heat extraction ability of ACE. Again, a chart was created to aid engineers in their preliminary assessments of the thermal stability of permafrost underneath ACE, based on measured or estimated site soil and temperature data.

Additional charts will be developed for other convective mitigation strategies for embankments built on thaw-sensitive permafrost.

Airports: Iqaluit, Kujjuaq and other Nunavik airports

<u>Iqaluit</u>

The Iqaluit international airport is the hub for air transport in the eastern Canadian Arctic, a part of the country without any road connection with the South. Built in the urgency during World War II, the airport was enlarged during the subsequent years of civil and military operations. Its paved runway can welcome all the types of aircrafts that fly in transit along the Arctic routes; it is also widely used by private, commercial and military aviation. The airport is key strategic infrastructure for Canada.

Over its existence, damages occurred on a recurrent basis by structural failures associated with the presence of permafrost and caused by ground freezing, thawing and thermal contraction processes related to the Arctic climate. The runway, the taxiways and the aprons are impacted by heave and subsidence due to the annual freezing and thawing of the active layer. Some vast areas underneath the infrastructure, where the soil is ice-rich, are very thaw-sensitive and potentially unstable. The airport underwent repairs and upgrades repeatedly. Historical records also state the recurring repairs of important and numerous frost cracks in the paved surfaces caused by the winter thermal contraction of underlying ice wedges. Underneath these frost cracks, the partial melting of these wedge-shaped ice masses in the ground causes linear settlements, with negative impacts on the running surface of the runway.

Since the early 1990s, the climate has warmed significantly. This region has seen an increase of about 2°C in the past 26 years and the climatic scenarios forecast a possible additional increase of 1 to 4 °C in winter and 0.5 to 2 °C in summer by 2030.

Because of the new concerns related to global warming in permafrost environments and the risks associated with thawing permafrost, the Iqaluit airport was the object of a detailed study by Centre d'études nordiques (CEN) of Université Laval that started in 2010 with co-funding from Transports Canada and the Government of Nunavut (GN). The results of that study brought a wealth of new knowledge and data on the permafrost conditions under the infrastructure.

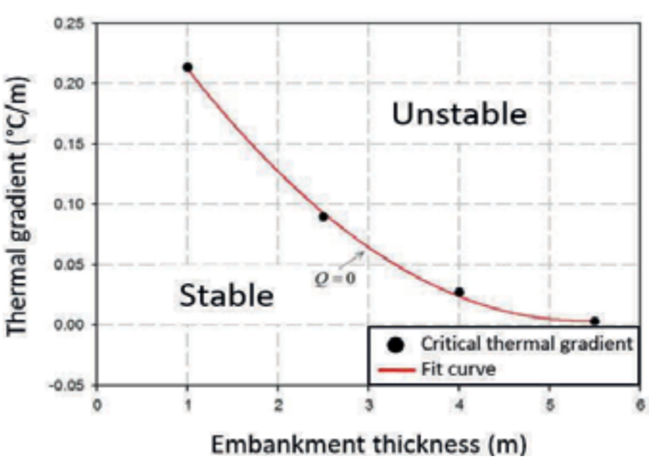

Figure 8. Critical thermal gradient (yearly average) as a function of embankment thickness, to estimate heat balance at the soil/embankment interface.

The study's report explains how the infrastructure itself is affecting the stability of permafrost through its impact on ground temperature regime and terrain drainage. The numerical modelling done in the study also demonstrates that climate change and thawing of permafrost are still likely to provoke serious damage to the infrastructure in the coming years (Mathon-Dufour and Allard, 2015).

This newly acquired geoscientific data on the Iqaluit airport's permafrost has oriented risk analyses; it supported choices of adaptation strategies implemented during the improvements done by the Arctic Infrastructure Limited Consortium in 2016 and 2017. For instances a decision was made to build a new taxiway A to replace the one that was on ground impossible to restore and a number of large furrows and cracks were repaired and equipped with insulation. The end-result is a modern infrastructure that is now better adapted to the impacts of climate warming.

The research project offered a unique opportunity to install monitoring instrumentation under the runway, the taxiways and some aprons. Those instruments currently record ground temperatures both under paved and unpaved terrain surfaces. They also record ground water levels in the active layer above the permafrost under the runway in order to assess how soil water flow (a heat carrying vector) affects the permafrost temperature regime and may accelerate thaw with possible damaging effects.

All the gathered information pertaining to surficial geology, permafrost characterization results, instrument location, surface observations of damages, historical repairs, ground temperatures, soil water levels, etc. is now stored in a GIS application ready for interrogation and use by the Government of Nunavut, the airport operators and any other potential stakeholder. The temperature records are available to support further thermal modelling. Observations of change in the temperature and groundwater regime can be used for pre-warning of potential impacts to come. The geodatabase and the data acquisition system in the field were designed to be operational for several years to come, with some routine maintenance, as just reported (Mathon-Dufour and Allard, 2018).

In September 2017, more instrumentation was set in place in wells drilled in 2016 and a data acquisition program is now being started for the coming years. In association with the risk analysis approach reported below, the program objectives are:

- To provide an annual state of situation of the stability of the infrastructure over permafrost.
- To assess the performance of the additions (e.g. taxiways, ditches) and adaptation techniques (e.g. behavior of repaired cracks) made at the airport in 2016 and 2017.
- By monitoring ground temperatures and groundwater variations, to provide a recurrent evaluation of the risks that the infrastructure, or more sensitive parts of it, are facing on the short (1 year), medium term (several years) and long term (future climate change).
- To provide necessary information on observed processes related to heat transfers and permafrost impacts in order to select the best designs of engineering solutions for maintenance or for eventual repairs, if needed.
- To support planning of the strategic maintenance of the airport.

Figure 9 is a map of the transformation that were brought to the upgraded infrastructure and a location plan of the installed monitoring instrumentation.

<u>Kuujjuaq</u>

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 Transport Canada are 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.

<u>Other Nunavik airports</u>

Elsewhere in Nunavik, we have been monitoring again in 2017 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). We are preparing for continuing this collaboration with the Québec Government. A major research site in 2018 will be the Tasiujaq airport and access road whch will be re-built almost anew following recommendations and engineering designs (reduced embankment slopes) developed in te previous years of this research project.

One major observation stemming out of the long-term monitoring or airports and roads on permafrost is the extreme importance of inter-annual climate variability for the stability of those infrastructures. For instance, the extremely warm summer of 2010 in northeastern Canada had impacts by provoking greater active layer depths and thaw settlements across Nunavik. The colder years of 2014-2017 have brought back the active layer base at shallower depths and helped maintain the permafrost table within embankments, thus impeding damages. This shows the extreme sensibility of runways and roads to climate variations and the associated risk of generating high maintenance coast on the short term. Modelling is also planned to better discriminate between the true performance of the adaptive engineering designs and the thermal control of climate variations.

Development of innovative approaches and technologies for permafrost research

New methods geophysical methods to measure liquid water content in permafrost

In June and July 2017, the University of Carleton team installed customised pipes in permafrost for measuring liquid water content as well as new instruments for tracking surface heave and subsidence near Yellowknife. They also generated precise site description for the observational plots around Yellowknife and experimented with surveying to quantify surface ambiguity on e.g., the impact of spatially variable moss cover on top of the soil. Subsequently, they established a new cluster of observational sites around KDI exploration camp in the tundra-taiga transition. As a partnership with the Northwest Territories Geological Survey, this campaign resulted in 12 boreholes instrumented with thermistor chains and well described and surveyed plots.

In November 2017, experimental measurements of Spectral Induced Polarization (SIP) have been performed near Yellowknife by project personnel (Gruber) and collaborators from the Planetary Science Directorate, Southwest Research Institute, Boulder, CO, USA (Grimm, Stillman). SIP works similar to Electrical Resistivity Tomography (ERT) and has the additional capability to uniquely identify ice.

A novel instrument tracks vertical displacement of the soil surface at three test sites near Yellowknife since July 2017. First data recovered in November shows an approximate accuracy of +/- 0.5mm for hourly data and diverse magnitudes and timing of movement. This technique will be important to better and more fully understand the subsurface energy balance as well as support the interpretation of remotely sensed data in terms of surface movement.

The customised sensors for tracking liquid water content in permafrost have been installed in September and read in November. They reveal differing freezing behaviour in differing stratigraphic units and appear to be functioning well. If this type of observation is successful in the long run, it will become an important complement to temperature observations.

Launching of a new datalogger system by a start-up company

In 2017, a new generation of Canadian datalogger to record permafrost (and other environments) temperatures was launch as a spinoff of the team's field experience. Launched by E. L'Hérault and M. Lemay, LogRSystems produces a light weight (0.5 kg), small size cylindrical (73 mm OD, 175 mm long) datalogger small enough to fit into a plastic tube set in a drill hole (Figure 10). The battery life spans ten years and the 16 or 32 channels can record data for several years on an hourly time interval (32 M-bits flash memory). A unique product on the market.

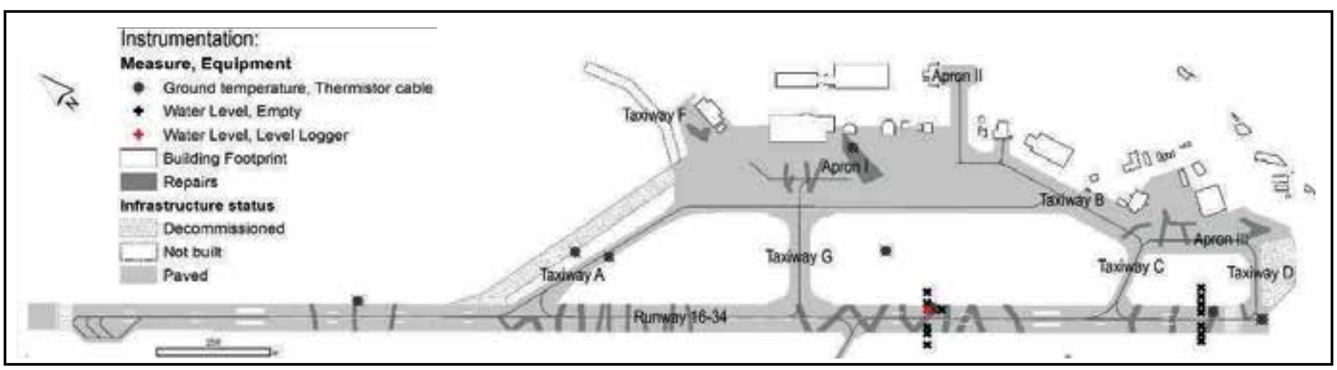

Figure 9. Map of changes and repairs done at Iqaluit airport to upgrade the facility and adapt it to climate warming. The map shows also the location of the monitoring instrumentation listed in the table.

To us, the greatest advantage is the abandonment of the needs for buried wires under runways and roads, solar panels and protection boxes. Not only the cost of an installation is reduced, but also the instrument can be set underneath airport runways without any surface structure, which allow meeting airport safety regulation standards.

Linkages with Laval University's Sentinel North program

NIs Allard, Doré and Calmels are key participants together with physicist 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. Communication networks dedicated to monitoring ecosystems and infrastructures have the potential to provide tremendous capabilities: real-time observation of climate change impact, hazard detection, early warning of risks, assessment of performance of applied adaptive designs, and enabling fast decision making to maintain infrastructure. Sensors placed by in Arctic villages under roads and airport runways yield critical information 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.

In 2017, first tests were run in Salluit, a community where a field research station and ancillary services exist, allows for easy access, tests, and on-site improvements. The tests make use of the new Tamaani wireless network of Kativik regional Government to have the instrument scattered in the community to communicate between each other and with a central base station (S. Bouchara's Masters thesis). This work feeds another master's thesis (S. Gauthier) that creates and GIS-Based information interface to make available the data and the information to stakeholders in real time.

DISCUSSION

Over the past three years, project members have addressed 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 at various scales, from country-wide Nunavik to village scale, 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.

Figure 10. The UlogC16-32 from LogR Systems being set into a thermistor cable casing.

Community mapping of permafrost went unto a new level of research, i.e. improving previously acquired knowledge and increasing the outreach effort in communities. Communities still express their needs for such studies. However, hazard mapping and assessments to protect public safety and for planning emergency measures (if needed) are more and more 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 Northerners for assessing the impacts of climate change on their own community infrastructure.

Technological advances over three years were made on several fronts: improving permafrost characterization with Ct-Scan, drilling techniques, soil respiration chambers, database building, designing monitoring set-ups under runways and, finally, the launching of a new model of datalogger by a spinnoff enterprise.

CONCLUSION

Given the allocated budget, the project met its main objective of making a contribution to the increase of the level of basic and practical knowledge on permafrost issues. Solutions where identified to specific infrastructure and community land use planning issues. Innovative research approaches were developed and, most importantly, knowledge was shared with regional governments, decision makers and members of northern communities. Most importantly, learning opportunities to the upcoming generation of Inuit. Finally, many graduate students obtained degrees through their involvement in this project.

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REFERENCES AND PUBLICATIONS

Allard, M. et Mathon-Dufour, V (2017) Suivi de l'évolution des conditions de pergélisol et de la vulnérabilité des infrastructures aéroportuaires du MTMDET au Nunavik dans le contexte des changements climatiques. Article de vulgarisation scientifique présenté au Ministère des transports, de la mobilité durable et de l'électrification des transports du Québec, Centre d'études nordiques, Université Laval, 5 p.

Allard, M., Valérie Mathon-Dufour, Denis Sarrazin, Jonathan Roger et Sarah Aubé-Michaud. 2017. Suivi de l'évolution des conditions de pergélisol et de la vulnérabilité des infrastructures aéroportuaires du MTMDET au Nunavik dans le contexte de CC. Rapport final au Ministère des transports, de la mobilité durable et de l'électrification des transports du Québec, Centre d'études nordiques, Université Laval, 179 p.

Aubé-Michaud, S., Allard, M., L'Hérault, E. et Mathon-Dufour, V., 2017. Identification des risques actuels et appréhendés sur le territoire des communautés du Nunavik en fonction des changements climatiques – phase 1: Document synthèse: Inukjuak. Rapport final, Centre d'études nordiques, Université Laval, 52 p.

Aubé-Michaud, S., Allard, M., L'Hérault, E. et Mathon-Dufour, V., 2017. Identification des risques actuels et appréhendés sur le territoire des communautés du Nunavik en fonction des changements climatiques – phase 1: Document synthèse: Ivujivik. Rapport final, Centre d'études nordiques, Université Laval, 49 p.

Aubé-Michaud, S., Allard, M., L'Hérault, E. et Mathon-Dufour, V., 2017. Identification des risques actuels et appréhendés sur le territoire des communautés du Nunavik en fonction des changements climatiques – phase 1: Document synthèse: Kangiqsualujjuaq. Rapport final, Centre d'études nordiques, Université Laval, 60 p.

Aubé-Michaud, S., Allard, M., L'Hérault, E. et Mathon-Dufour, V., 2017. Identification des risques actuels et appréhendés sur le territoire des communautés du Nunavik en fonction des changements climatiques – phase 1: Document synthèse: Kangiqsujuaq. Rapport final, Centre d'études nordiques, Université Laval, 60 p.

Aubé-Michaud, S., Allard, M., L'Hérault, E. et Mathon-Dufour, V., 2017. Identification des risques actuels et appréhendés sur le territoire des communautés du Nunavik en fonction des changements climatiques – phase 1: Document synthèse: Puvirnituq. Rapport final, Centre d'études nordiques, Université Laval, 56 p.

Aubé-Michaud, S., Allard, M., L'Hérault, E. et Mathon-Dufour, V., 2017. Identification des risques actuels et appréhendés sur le territoire des communautés du Nunavik en fonction des changements climatiques – phase 1: Document synthèse: Quaqtaq. Rapport final, Centre d'études nordiques, Université Laval, 57 p.

Aubé-Michaud, S., Allard, M., L'Hérault, E. et Mathon-Dufour, V., 2017. Identification des risques actuels et appréhendés sur le territoire des communautés du Nunavik en fonction des changements climatiques – phase 1: Rapport final, Centre d'études nordiques, Université Laval, 10 p.

Boisson, A. (2017) Évaluation des risques côtiers au Nunavik dans un contexte de changements climatiques. Rapport pour le compte du Ministère des Transports, de la Mobilité durable et de l'Électrification des transports. Centre d'études nordiques, Université Laval, 18 p.

Boisson, A. and Allard, M. (2018) Quaternary Hydrodynamic Contexts of the Emerging Coasts of Nunavik (Northern Quebec, Canada). In: Shim, J.-S.; Chun, I., and Lim, H.-S. (eds.), Proceedings from the International Coastal Symposium (ICS) 2018 (Busan, Republic of Korea). Journal of Coastal Research, Special Issue No. XX, pp. X–X. Coconut Creek (Florida), ISSN 0749-0208 (accepté).

Brooks H., Doré G. and Lemieux C., 2015, Quantitative Risk Analysis of Linear Infrastructure on Permafrost: State-of-the-Practice Literature Review. Report for Transport Canada, April, 21 pp.

Brooks H., Doré G. and Lemieux C., 2017, Quantitative Risk Assessment of the Iqaluit International Airport, Iqaluit, Nunavut. Report for Transport Canada, September, 53 pp.

Brooks H., Doré G. and Locat A., 2017, Soil Bridging Effects within Permafrost-Supported Embankment Infrastructure. Journal of Cold Regions Engineering.

Brooks H., Doré G., Smith S.L., 2018, Permafrost Geotechnical Index Property Variation and its Effect on Thermal Conductivity Calculations. Cold Regions

Science and Technology, 148, p. 63-76, https://doi.org/10.1016/j.coldregions.2018.01.004.

Brown, Nicholas. 2017. Towards improved monitoring of changing permafrost by estimating soil characteristics from ground temperature time-series. M.Sc. thesis, Carleton University, Ottawa, Ontario.

Calmels, F., Roy, L.P., Grandmont, K. and Pugh, R. 2018. Monitoring Culvert Insulation, the Dempster Highway, YT. Yukon Research Centre, Yukon College, 40 p.

Camels, F., Roy, L.P., Grandmont, K. and Pugh, R. 2018. A Summary of Climate- and Geohazard-Related Vulnerabilities for the Dempster Highway Corridor. Yukon Research Centre, Yukon College, 200 p.

Camels, F., Roy, L.P., Laurent, C. and Horton, B. 2017. Investigation of Dempster Highway Sinkholes: km 82 and Two Moose Lake. Yukon Research Centre, Yukon College, 66 p.

Doré G., Niu F. and Brooks H., 2016, Adaptation methods for transportation infrastructure built on degrading permafrost. Permafrost and Periglacial Processes, doi: 10.1002/ppp.1919.

Gagnon, S., E. L'Hérault, M. Lemay, and M. Allard (2016), New low-cost automated system of closed chambers to measure greenhouse gas emissions from the tundra, Agricultural and Forest Meteorology, 228-229, 29-41, doi:10.1016/j.agrformet.2016.06.012.

Gagnon, S., M. Allard and A. Nicosia (2017), Diurnal and seasonal variations of tundra CO_2 emissions in a polygonal peatland near Salluit, Nunavik, Canada, Arctic Science, 4:1-15, doi: 10.1139/AS-2016-0045.

Lemay, M.-A., L. Provencher-Nolet, M. Bernier, E. Lévesque, S. Boudreau. 2018. Spatially explicit modelling and prediction of shrub cover increase near Umiujaq, Nunavik. Accepted Ecological Monograph January.

L'Hérault, E. et M. Allard (2018). Cartographie des conditions de pergélisol au Québec en fonction des paramètres géomorphologiques, écologiques, et des processus physiques liés au climat: 2e édition. Réalisé pour le compte du ministère de la Faune, des Forêts et des Parcs, Centre d'études nordiques, Université Laval (en prep).

L'Hérault, E., M. Allard et M. Lachapelle. Fondations sur pergélisol. In Construction d'habitations au Nunavik: Guide de bonnes pratiques, Société d'Habitations du Québec , deuxième édition. Québec: Gouvernement du Québec (sous presse).

Mathon-Dufour, V., Allard, M. and L'Hérault, E. (2017) Scientific support to the performance monitoring and maintenance of the Iqaluit airport. Progress Report presented to Transports Canada. Centre d'études nordiques, Université Laval, Québec. 17 p.

Mathon-Dufour, V., Allard, M. et Sarrazin, D. (2017) Adaptation d'infrastructures aéroportuaires aux changements climatiques en milieux nordiques: Aéroport de Kuujjuaq. Synthèse et analyse des données 2015-2016. Rapport annuel présenté à Transports Canada et TPSGC. Centre d'études nordiques, Université Laval, Québec. 68 p.

Mathon-Dufour, V., Allard, M. et Sarrazin, D. (2017) Mise à jour et adaptation de l'instrumentation de suivi environnemental en vue de la réfection de l'infrastructure aéroportuaire de Kujjuaq, Nunavik. Rapport de mission présenté à Transports Canada et TPSGC. Centre d'études nordiques, Université Laval, Québec. 10 p.

Perreault, N., E. Lévesque, D. Fortier, D. Gratton and L. Lamarque. 2017. Remote sensing evaluation of High Arctic wetland depletion by thermo-erosion gullying. Arctic Science, 3(2): 237-253.

Tremblay, M., 2017. Étude de la distribution de l'arbuste érigé Salix richardsonii à sa limite nordique dans l'est de l'Arctique canadien. MSc thesis, Université du Québec à Trois-Rivières, 91p.

EFFECTS OF CLIMATE SHIFTS ON THE CANADIAN ARCTIC WILDLIFE: ECOSYSTEM-BASED MONITORING AND MODELLING

Project Team

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ABSTRACT

Arctic ecosystems are undergoing major changes related to climate shifts. To understand these transformations, this project is monitoring 35 wildlife populations (primarily mammals and birds) at 12 study sites in the Eastern Canadian Arctic, including Rankin Inlet, Coats Island, Southampton Island, Igloolik Island, and Bylot Island. Field observations are carried out to better understand ecological processes determining the response of wildlife to climate shifts. In addition, the ecosystem-scale exposures and sensitivities of the tundra to climate change are identified through modeling in order to estimate and map, at a regional scale, the ecological vulnerability of the tundra to climate shifts. Northern Quebec is used as a first case study to map tundra vulnerability, with plans to expand this work to larger areas. Project members work in collaboration with 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.

KEY MESSAGES

- We made final progress in 2017 toward a modeling of the response of tundra biodiversity to climate change, using northern Nunavik as case study. The borealisation of the northern tip of the Ungava Peninsula, which is now underway, should lead to strong reorganization of local ecosystems.
- We developed models highlighting the importance of considering multiple interacting effects when predicting changes in wildlife populations experiencing climate change.
- We found both circumpolar and regional drivers of caribou population structure encompassing historical and current environmental changes. This will help to guide management and population sampling in the Arctic.
- We showed that timing of ice-breakup near an arctic-nesting common eider colony strongly affects the population breeding output. However, the effect of arctic sea ice dynamics is modulated by the bird body condition, which partly depends on climatic events encountered away from the Arctic.
- We strengthened our international research network ArcticWEB (http://arcticweb-project.org/index.html) and expanded our circumpolar ecological observations and experiments dealing with the cascading impacts of indirect interactions in the arctic tundra.
- We coordinated a circumpolar effort to harmonize monitoring of Arctic fox (a key tundra species) at 34 international sites from all Arctic Council countries. This allowed the production of protocols that will gradually be adopted at the circumpolar scale (Berteaux et al. 2017).
- Technological progress is revolutionizing wildlife research and we have continued to participate to this in 2017: we have tracked several northern wildlife species with miniaturized satellite loggers, we developed scripts able to analyze pictures taken from automatic cameras, 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 started new work at the Canadian Forces Station in Alert, with support from the Department of National Defence and the Canadian Armed Forces, in order to strengthen knowledge of High Arctic wildlife and develop a Biodiversity Management Plan for CFS Alert.
- We showed that overabundant arctic-nesting snow geese can have negative effects on other bird species through shared predators like foxes. Managers can use our results to better justify changes in the hunting regulations associated to overabundant species (Lamarre et al. 2017).
- We synthesized effects of changing permafrost and snow conditions on tundra wildlife and identified the critical places and times at which further research efforts should concentrate.
- We produced new maps highlighting the potential effects of climate change on the tundra biodiversity in Nunavik and provided users and the scientific community with important data sets about climate and biodiversity of northern Nunavik. This include the publication in NordicanaD of six datasets describing for the tundra of Nunavik (1) the distribution of birds and mammals during 1981-2010, (2) the functional traits of mammals and birds, (3) the trophic relations of biodiversity, (4) the potential future distribution of birds and mammals in Nunavik projected under climate change, (5) 27 gridded climate variables projected during the 21st century under 10 climate change scenarios, and (6) 27 gridded climate variables for 1981-2010.

RESEARCH 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

The project members have conducted many knowledge mobilization activities, from oral presentations in scientific conferences, to media inteviews and community outreach activities. The main activities are listed below:

- 46 presentations at scientific conferences
- 18 interviews with online, print and broadcast media
- 8 Northern research partners mentored
- 11 meetings with Wildlife management decision-makers (Nunavut)
- 2 popular science articles written based on our research
- 3 meetings with Biodiversity conservation decision-makers (Quebec)
- 3 Northern communities (Cape Dorset, Coral Harbour, Resolute Bay) visited for results sharing workshops
- Meeting in Pond Inlet with community representatives during one week in July 2017
- Extensive consultations with representatives from various community organization over a 2-week that culminated on a 2-day workshop (35 attendees) in Pond Inlet in late January/early February 2018. The aim of the consultation was to plan joint future projects on ecological monitoring in the North Baffin region with the community.
- Several presentations made in local schools by students in Pond Inlet and Resolute
- 1 Education Information Sharing workshops held in community schools (Arctic College in Iqaluit, High School in Coral Harbour)
- Creation of the northern biodiversity web site to share wildlife observations among community members (Inuktitut version at http://pondinlet.northernbiodiversity.ca/iu)
- Posting of multiple entries on the Facebook page of the Bylot Island research camp (https://www.facebook.com/goosecampbylot/)
- Organization of the 5th International conference in Arctic Fox Biology (12-15 October 2017, Rimouski) attended by 112 people from 11 countries
- Arctic Raptors Facebook page (https://www.facebook.com/ArcticRaptorsOfficial/) reached more than 2800 followers worldwide, several posts logged greater than 8000 views in 2017
- Organisation of the second ArcticWeb workshop (16-17 October 2017, Rimouski), attended by 20 researchers from six countries
- Organisation of science booths, outreach activities and diners in Pond Inlet (Nattinnak Visitor Centre and Northern Store). We presented research gears, maps, results and pictures about the Bylot Island ecological monitoring

INTRODUCTION

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) and where humans depend strongly on the natural world. Wildlife monitoring is thus critical to track ongoing ecological changes, and a good 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. Therefore our project has made great efforts to model arctic ecosystems and biodiversity, with emphasis on the tundra of Nunavik as case study.

ACTIVITIES

Time frame and study area

Field work was carried out from May to September 2017 at East Bay (Southampton Island), Rankin Inlet, Mary River (Milne Inlet to Steensby Inlet), Igloolik, Baker Lake, Coats Island, Alert, and Bylot Island. Boat-based bird and polar bear research was carried out in summer 2017 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 (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 on 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 arthropods and goose browsing in eight plots in Igloolik.

- Long-term monitoring of an ITEX site on Igloolik.
- Instalment of experimental plots in Igloolik to study environment-productivity-diversity relationships at a global scale (Nutrient Network).

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 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, and Baker Lake.
- 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 at Rankin Inlet.
- Banding of ca. 120 peregrines and rough-legged hawks at Rankin Inlet.
- Marking of 14 rough-legged hawks at Rankin Inlet.
- Monitoring of the reproductive activity of seven nests of rough-legged hawks (among 96 known potential nesting sites visited), five nests of peregrine falcons (among 10 known potential nesting sites visited), and one nest of gyrfalcon at Bylot Island.
- Sampling of 106 hawk pellets at Igloolik Island and Bylot Island.

Birds (shorebirds and passerines)

- ca. 160 1 km transects completed to estimate abundance of avian species using distance sampling.
- Monitoring of ca. 100 shorebird nests and ca. 65 passerine nests at Bylot Island.
- Marking of ca. 20 shorebirds and ca. 20 passerines at Bylot Island.
- Recovery of 10 geolocators on shorebirds (common-ringed plovers) on Bylot Island.
- Monitoring of the growth rate of 60 known-aged snow bunting chicks from 13 nests on Southampton Island.
- Monitoring of 116 shorebird and 15 passerine nests at Igloolik Island.
- Marking of 42 shorebirds at Igloolik Island.
- Monitoring of mercury levels in 50 shorebirds at Igloolik Island.
- Acoustic recordings of shorebird and passerine phenology at Igloolik and Bylot.
- Monitoring temporal and spatial variation in nest predation risk using artificial nests at Igloolik Island.

Birds (geese and seabirds)

- Monitoring of reproductive activity of 342 nests of snow geese at Bylot Island.
- Monitoring of reproductive activity of six nests of parasitic jaegers and 30 nests of glaucous gulls at Bylot Island.
- Banding of six long-tailed jaegers and recovery of six previously deployed geolocators at Bylot Island.
- Banding and re-sighting of 300 adult eider ducks on Southampton Island to estimate annual survival of birds in relation to disease, harvest, and weather conditions.

- Capture and banding of 3216 snow geese with leg bands, including 481 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 54 common eiders paired with hormone implants and egg collections (18 nests) to examine the influence of physiology on foraging behavior and reproductive success.
- 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 97 thick-billed murres from Coats Island nesting colony to identify key foraging habitat areas during the breeding season.
- Monitoring of the reproductive activity of 4 nests of long-tailed jaegers, two nests of parasitic jaegers, 10 nests of arctic terns and one nest of herring gull at Igloolik Island.
- Monitoring of the reproductive activity of 28 nests of geese or waterfowl at Igloolik Island.
- Banding of 5 long-tailed jaegers and two parasitic jaegers and deployment of seven geolocators on jaegers at Igloolik Island.
- Banding of 14 arctic tern and deployment of 14 geolocators on terns 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 at Bylot Island.
- Monitoring of short- and long-range movements of arctic foxes breeding on Bylot.
- Monitoring of lemming abundance and demography at Bylot Island (150 winter nests sampled; live-trapping of 25 brown lemmings and five collared lemmings during 4300 trapping days; snap-trapping of five brown lemmings and 1 collared lemming during 2100 trapping-days).
- 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.
- Monitoring relative abundance of herbivores using 10-20 faeces transects (Bylot Island, Igloolik Island).
- Survey of Canada Forces Station Alert to implement new mammal monitoring activities (arctic hare, arctic wolf, hermine, collared lemming, arctic fox, muskox, Perry caribou).

- Transect counts of Arctic hares (the most abundant herbivore of the regional ecosystem) at CFS Alert.

Syntheses

- Consolidation of the Arctic Falcon Specialist Group to facilitate data synthesis, recognized as priority focal ecosystem component by the Circumpolar Biodiversity Monitoring Program.
- 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.
- Publication of first synthesis of circumpolar Arctic fox monitoring.
- Synthesis across several circumpolar study sites through involvement in the Circumpolar Seabird Working Group of the Arctic Council.

Figure 1. Adult female peregrine falcon caching a Common Quail (Coturnix coturnix) that had been delivered to nestlings at a supplemented nesting territory (photo: E. Hedlin).

- Coordination of the circumpolar project "indirect trophic interactions" to understand and predict cascading effects in arctic terrestrial vertebrate communities.
- Coordination of ArcticWEB, a network to help determine concerted research efforts in terrestrial arctic ecology.
- Publication 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

Nestling survival in peregrine falcons (Objective 1)

Our long term project on a population of peregrine falcons breeding around Rankin Inlet has chronicled a steady decline in annual productivity over 30 years (Franke et al. 2010). By documenting the direct effects of summer rainfall on nestling mortality, a recent study using nest boxes indicated that an increasing frequency of heavy rainfall partially explained the observed decline (Anctil et al. 2014). However, nestling mortality associated with starvation was documented in nestlings raised in nest-boxes and protected from rainfall. Therefore, over five years (2013-2017), we food supplemented 168 individuals from 51 broods, and monitored 186 individuals from 58 broods that were not supplemented. Each year, we randomly selected broods and supplemented their diet with commercially produced Common Quail (*Coturnix coturnix*) equal to 50% of the brood's age-specific energetic demand (Figure 1).

Food supplementation resulted in higher nestling survival (Figure 2) which suggests that nestlings were generally food limited during the breeding season. We also found a strong negative relationship between hatch date and nestling survival (Figure 2).

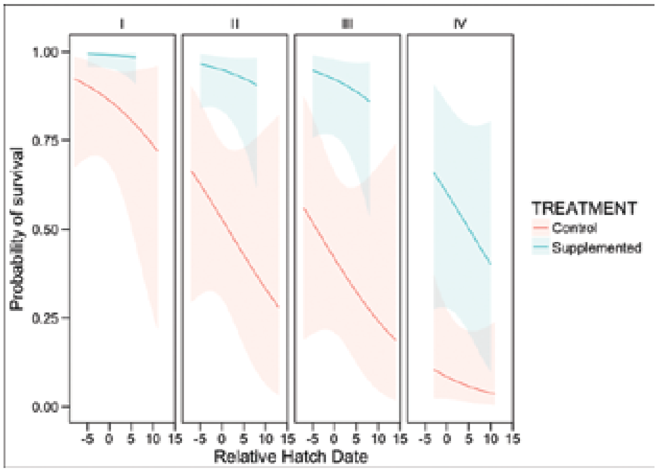

Figure 2. Survival probabilities for supplemented and control nestlings monitored from 2013-2017 as a function of hatch order, treatment, and relative hatch date (hatch dates standardized against the yearly median). Error lines depict the 95% confidence intervals. Mean asynchrony for hatch 1: 0±0, hatch 2: 0.64±0.73, hatch 3: 1.67±1.14, hatch 4: 2.8±1.70.

Population structure of a key arctic herbivore, the caribou (Objective 1)

Genetic differentiation among populations may arise from local adaptations, geographical isolation, or both. Yet quantifying the relative strength of these two mechanisms of differentiation is challenging. We did so and analyzed the entire distribution range of caribou. Our results indicate that genetic differentiation is predominantly explained by historical isolation and increasing resistance of the environment such sea ice loss. Our results (Figure 3) indicate that conservation policies aimed to preserve caribou-reindeer populations should carefully consider the different herds, particularly when management practices involve translocations or reintroductions of individuals that belong to populations adapted to specific local environmental conditions. This is specifically the case of the threatened boreal caribou in North America that suffer high anthropogenic pressures, but could be

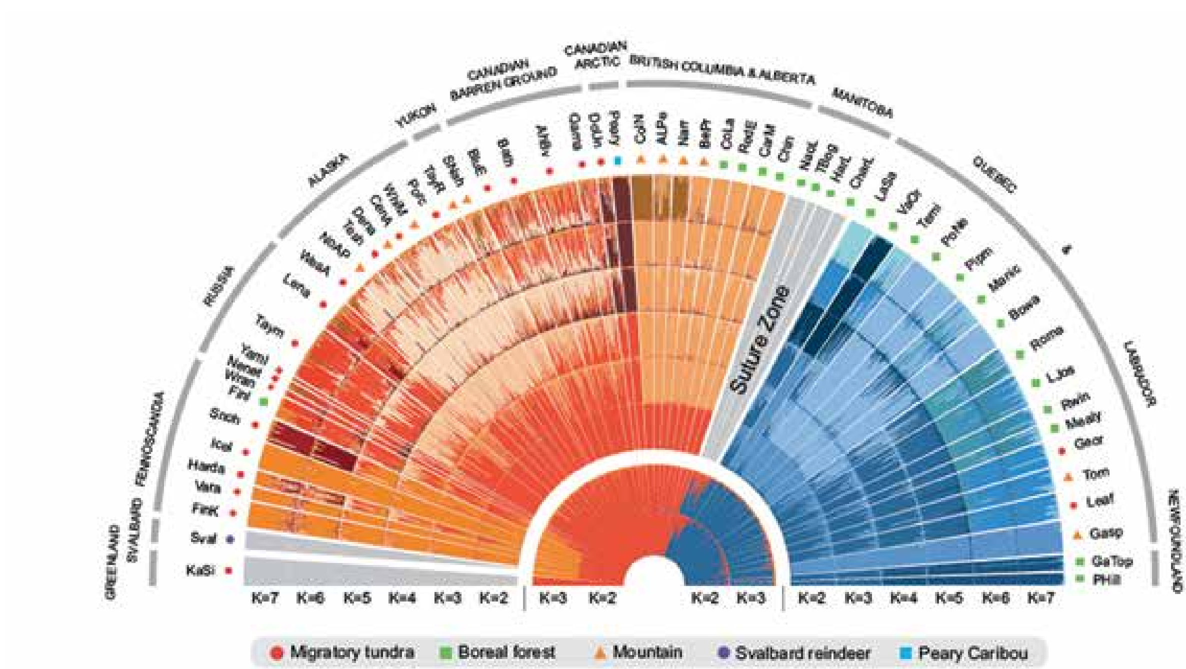

Figure 3. Gene based grouping of 1297 caribou and reindeer. Each individual is represented by a thin vertical line that is partitioned into colored segments that indicate the proportional assignment of each individual to the groups with that color. Individuals are grouped into main regions and herds. Red diamonds correspond to introduced or semi-domestic migratory caribou-reindeer.

extended to all others. Any program of reinforcement of declining boreal caribou populations should consider that two distinct independent evolutionary lineages are living in close vicinity in the continuous range of the boreal forest and source populations for translocations should be carefully selected. While our work provides some indications of local adaptation in caribou, additional information is required to understand how the unprecedented speed of human-induced environmental change will affect its levels of genetic diversity and the capacity of the populations to cope with environmental changes

Physiological mechanisms driving foraging behaviour and reproduction (Objective 2)

To monitor female common eider (*Somateria mollissima*) movement and diving behaviour, we have deployed GPS devices on hens captured at East Bay Island during the pre-breeding period for the past four years. This detailed tracking data allows us to monitor their foraging behaviour between arrival at the colony and laying date, which is a critical period for the success of their reproduction. During the pre-laying period females need to accumulate significant fat stores and must optimize their foraging behaviour to maximise their reproductive success. Previous research at this colony has shown that females with higher fattening rates have earlier laying dates, larger clutch sizes and higher duckling survival. Further, we have shown that elevations of corticosterone, an energetic hormone, also led to earlier breeding and higher reproductive success suggesting this is an important mechanism affecting fattening rates. To test if corticosterone is indeed affecting foraging, in 2016 and 2017, we coupled corticosterone manipulations with GPS tracking, allowing us to document the effects of this hormone on foraging behaviour at different reproductive stages. Our preliminary results show that females with experimentally increased levels of corticosterone spent more time foraging while growing the yolks of their eggs (called rapid follicle growth; RFG) than females with natural corticosterone levels (Figure 4). In terms of habitat use, there also appears to be different foraging strategies among individuals, with some females concentrating their foraging effort in localized areas while others have a more varied use of East Bay. We will soon test whether corticosterone affects this behaviour.

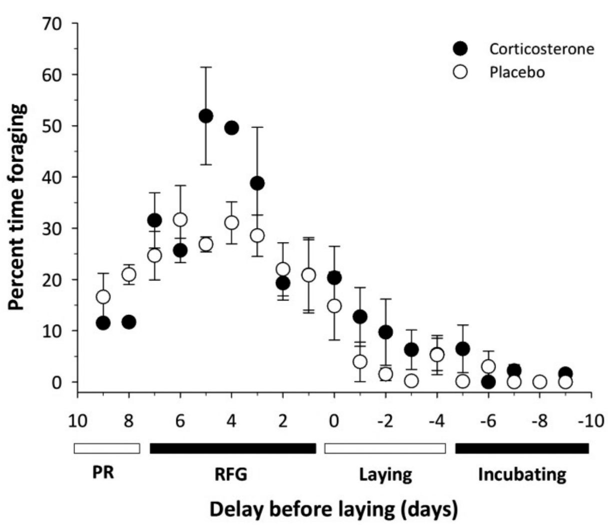

Figure 4. (left) The influence of corticosterone, an energetic hormone, on time spent foraging by common eider hens at different reproductive stages. PR = pre-recruiting hen (not yet committed to reproduction), RFG = rapid follicle growth, (right) incubating hen.

The impact of nest predation by polar bears on common eider populations (Objective 2)

Because of sea-ice loss, we have shown that polar bear predation on common eider eggs has been increasing at East Bay Island and in other locations across the Arctic. Yet the number of eiders nesting at East Bay Island has remained relatively stable over the last five years. We have used computer simulation models to understand how polar bears might be affecting common eider populations and why the population at East Bay Island is not declining as expected. Our models suggest that climate warming may slightly increase the number of eggs laid by eiders, as well as the number of eiders that initiate nesting, which could offset the effect of polar bear predation (Figure 5). However, our models also suggest that eiders might disperse to different islands to avoid polar bears.

Effects of sea ice dynamics on common eider breeding output (Objective 2)

Using long term monitoring data, we investigated the influence of sea ice conditions and individual body condition on the breeding output of migrating arctic-nesting common eiders. Using Radarsat satellite images acquired from 2002 to 2013 we estimated the proportion of open water in the intertidal zone in early summer to track the availability of foraging areas for pre-breeding eider females. Timing of ice-breakup varied by up to 20 days across years and showed strong relationship with both breeding propensity (Figure 6) and the timing of laying: fewer eiders were resighted nesting in the colony and laying was also delayed in years with late ice-breakup.

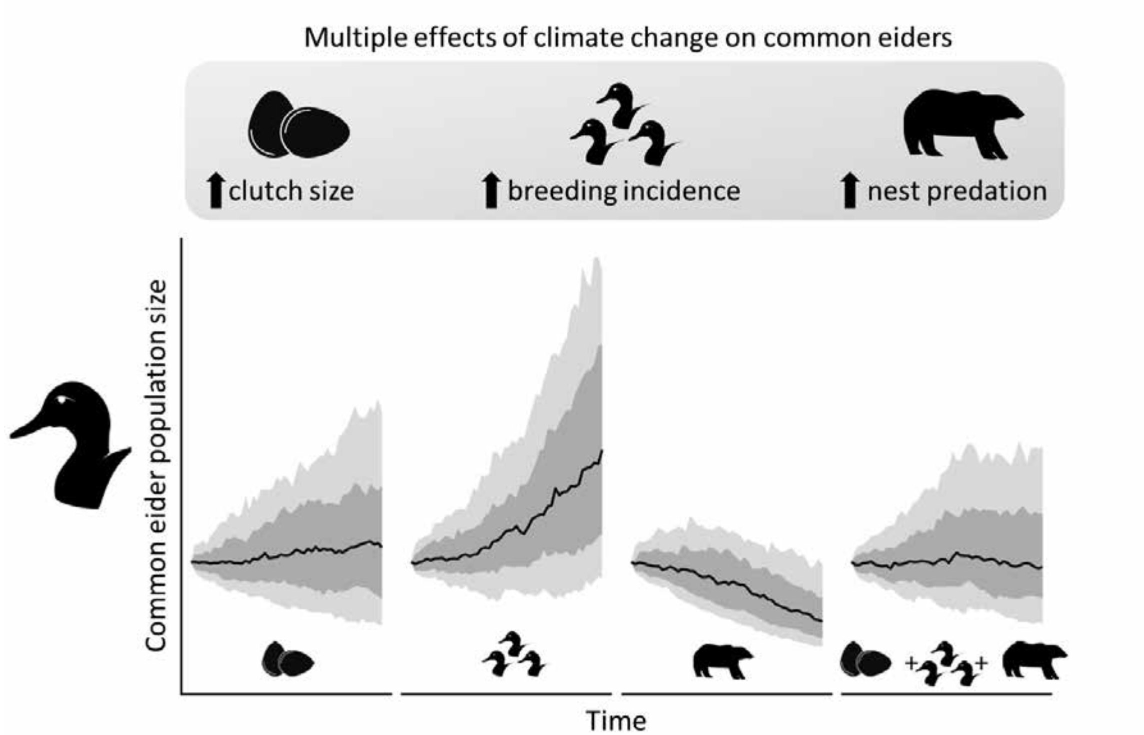

Figure 5. Multiple effects of climate change on common eiders (based on information presented in Dey et al. in revision).

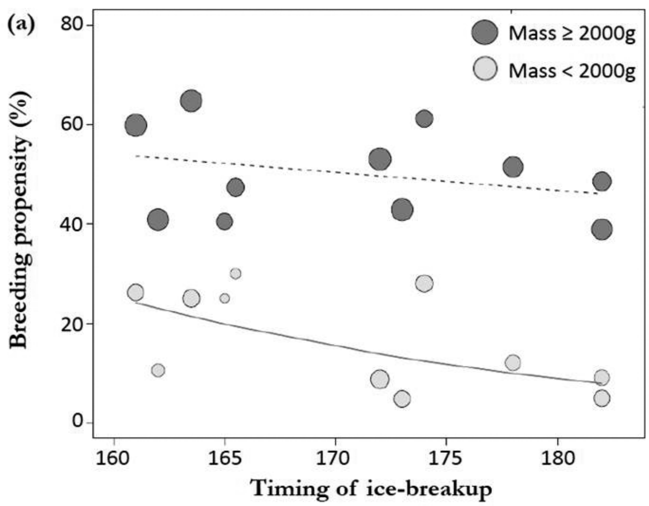

Figure 6. Relationship between the timing of spring sea ice break-up and common eider breeding propensity (i.e., the proportion of adult females initiating breeding). The relationship is stronger for females arriving at the nesting colony in poor condition (<2000 g; light grey circles). Ice-breakup is defined as the day of 1% of open water in the Bay surrounding the eider nesting colony. Circle sizes are proportional to log N.

Potential effects of climate change on the tundra of Nunavik (Objectives 3 and 4)

Using climate niche modeling (Berteaux et al. 2010, 2018), we estimated potential changes to the biodiversity of the tundra of Nunavik and expressed these changes using metrics describing species interactions within ecosystems. In particular, we assessed potential changes in the number of trophic links within food chains under two scenarios of climate change. Results (Figure 7) show that the number of trophic links should increase over time, as new species invade the tundra when the climate improves for them. Not surprisingly, changes in the number of trophic links are more pronounced in the most dramatic scenarios of climate change. Interestingly, changes are spatially heterogeneous, with the central parts of the study area showing more intense changes than peripheral parts.

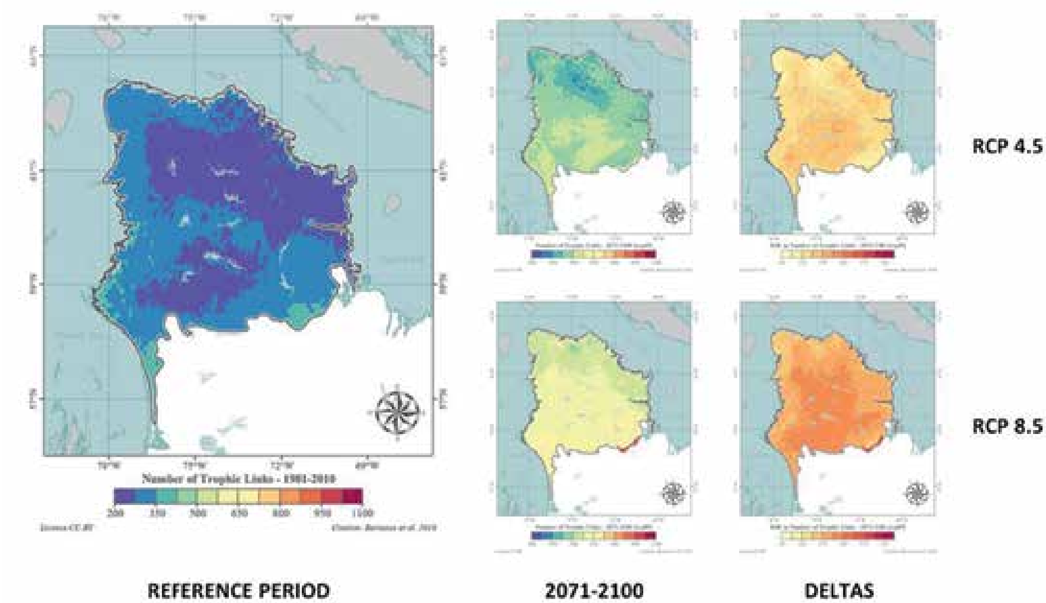

Figure 7. Potential changes in the number of trophic links within trophic networks of the tundra of Nunavik. Projections into the future were estimated under two RCP (Representative concentration pathways) representing a moderate (RCP 4.5) and strong (RCP 8.5) intensity of climate change. The number of trophic links for the reference period (1981-2010) appears on the left map, while the number of trophic links for 2071-2100 appears on the central maps for RCP 4.5 (top) and RCP 8.5 (bottom). Deltas indicate the potential differences between 2071-2100 and 1981-2010.

DISCUSSION

Nestling survival in peregrine falcons (Objective 1)

Our findings suggesting that Peregrine Falcons nestlings were generally food limited at Ranking Inlet during the breeding season are consistent with Anctil et al. (2013). The relationships we found were also documented in other populations (Brinkhof et al. 1993, Brinkhof and Cave 1997, Dzus and Clark 1998, Drent 2006, Verhulst and Nilsson 2008), and in some cases have been linked to seasonal declines in food availability (Brinkhof and Cavae 1997). We will pursue this research to evaluate whether our understanding of peregrine decline is now complete or if more studies are required to investigate additional factors.

Population structure of a key arctic herbivore, the caribou (Objective 1)

Our results indicate that conservation policies aimed to preserve caribou-reindeer populations should carefully consider the different herds, particularly when management practices involve translocations or reintroductions of individuals that belong to populations adapted to specific local environmental conditions. This is specifically the case of the threatened boreal caribou in North America that suffer high anthropogenic pressures, but could be extended to all others. Any program of reinforcement of declining boreal caribou populations should consider that two distinct independent evolutionary lineages are living in close vicinity in the continuous range of the boreal forest and source populations for translocations should be carefully selected. While our work provides some indications of local adaptation in caribou, additional information is required to understand how the unprecedented speed of human-induced environmental change will affect its levels of genetic diversity and the capacity of the populations to cope with environmental changes (Jenkins et al. 2018, Yannic et al. 2017).

Physiological mechanisms driving foraging behaviour and reproduction (Objective 2)

Our preliminary results suggest that the level of stress hormones can affect foraging behaviour prior to the start of incubation. In the context of climate change, it is critical to understand whether eiders are able to adjust their foraging behaviour in response to changing sea ice conditions. We have shown that the timing of ice break-up affects foraging during the pre-breeding period which can have subsequent consequences for timing of breeding and reproductive success (Jean-Gagnon et al. In press). Understanding the physiological mechanisms driving foraging behaviour is an important step that will allow us to eventually model the possible consequences of changing ice conditions on eider foraging behaviour, reproductive success, and ultimately population viability.

The impact of nest predation by polar bears on common eider populations (Objective 2)

Our models show that climate-mediated increases in clutch size and breeding propensity might overcome the increase of nest predation by polar bears caused by sea-ice loss, leading to a relatively stable eider population over a 50-year period. These results highlight the importance of considering multiple interacting effects when predicting changes in wildlife populations experiencing climate change. Additionally, our models predict that eider colonies facing increased predation by polar bears are likely to become smaller as eiders disperse, which could have considerable impact on eggs and down harvesting by Inuit. We are continuing to investigate how polar bears will influence eiders as sea ice declines and how this will affect Inuit who harvest eiders.

Effects of sea ice dynamics on common eider breeding output (Objective 2)

We showed that the timing of ice-breakup strongly affects breeding output of arctic-nesting eiders. Timing of ice break-up in early summer, a likely proxy of food availability, is thus crucial for reproductive decisions in eiders. However, the effect of sea ice dynamics was modulated by the state (body condition) of females at arrival on the breeding grounds, which partly depends on environmental conditions encountered on their wintering grounds in southern Canada and West Greenland (Descamps et al. 2010). Combining scenarios of future Arctic sea ice dynamics and our results will enable a stronger predictive capacity in determining how Arctic-breeding sea birds respond to environmental conditions.

Potential effects of climate change on the tundra of Nunavik (Objectives 3 and 4)

Projecting potential changes to ecosystem metrics arising from climate change is interesting because such projections allow interpretations far beyond the species level. At the same time, these projections are challenging because their interpretation is not always intuitive. We showed that ecosystem structure and functioning will be strongly impacted by climate change in the tundra of Nunavik. We are still struggling, however, to determine whether these changes are positive (showing that ecosystems will adapt to new climates) or negative (showing that ecosystems will suffer from new climates). Improving our ability to interpret our findings will be critical as conservation decisions, such as those linked to Plan Nord (Berteaux 2013), will need to take into account climate change effects on northern biodiversity.

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. We have also added a new wildlife monitoring site (Canada Forces Station Alert). 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. 2017) through IRIS 2. This continues to strengthen the fundamental objective of the IRIS framework.

We have also integrated data from our field studies via predictive models of ecosystem 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.

Finally, at the end of this ArcticNet second phase, we have made great effort to publish our data and metadata into either the Polar Data Catalogue or other recognized alternative repositories, such as NordicanaD. This is a very important legacy to our project given that future generations of researchers and northern residents will no doubt want to understand how wildlife has changed since the end of the twentieth century.

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REFERENCES

Anctil, A., A. Franke, and J. Bêty. 2013. Heavy rainfall increases nestling mortality of an arctic top predator: experimental evidence and long-term trend in peregrine falcons. Oecologia:1-11.

Anctil, A., A. Franke, and J. Bety. 2014. Heavy rainfall increases nestling mortality of an arctic top predator: experimental evidence and long-term trend in peregrine falcons. Oecologia 174:1033-1043.

Berteaux D, et al. 2010. The CC-Bio Project: Studying the Effects of Climate Change on Quebec Biodiversity. Diversity 2:1181–1204.

Berteaux D., Gauthier G., Dominé F., Ims R.A., Lamoureux S.F., Lévesque E., Yoccoz N. In press. Effects of changing permafrost and snow conditions on tundra wildlife: critical places and times. Arctic Science 3:65-90.

Berteaux D. 2013. Québec's Large-Scale Plan Nord. Conservation Biology 27:242–243.

Berteaux, D., M. Ricard, M.-H. St-Laurent, N. Casajus, C. Périé, F. Beauregard, and S. De Blois. 2018. Northern protected areas will become important refuges for biodiversity tracking suitable climates. Scientific Reports, in press.

Brinkhof, M. W. G., A. J. Cave, F. J. Hage, and S. Verhulst. 1993. Timing of reproduction and fledging success in the coot *Fulica atra* - Evidence for a causal relationship. Journal of Animal Ecology 62:577-587.

Brinkhof, M. W. G., and A. J. Cave. 1997. Food supply and seasonal variation in breeding success: An experiment in the European coot. Proceedings of the Royal Society B-Biological Sciences 264:291-296.

Descamps, S., Yoccoz, N.G., Gaillard, J.-M., Gilchrist, G.H., Erikstad, K.E., Hanssen. S.A., Cazelles, B., Forbes, M.R. and Bêty, J. 2010. Detecting population heterogeneity in effects of North Atlantic Oscillations on seabird body condition: get into the rhythm. Oikos 119:1526-1536.

Dey CJ, Semeniuk CAD, Richardson E, McGeachy D, Gilchrist HG. Forecasting the impact of multiple effects of climate change on northern common eiders. Biological Conservation 220: 94-103.

Drent, R. H. 2006. The timing of birds' breeding seasons: the Perrins hypothesis revisited especially for migrants. Ardea 94:305-322.

Dzus, E. H., and R. G. Clark. 1998. Brood survival and recruitment of Mallards in relation to wetland density and hatching date. Auk 115:311-318.

Franke, A., Berteaux, D., Ferguson, S., Gauthier, G., Hutson, C., Marcoux, M., Martin, Z., Sahanatien, V., Statham, S., Szor, G., Tallman, R., 2017. Chapter 18: Climate change impacts on managed wildlife, in: IRIS 1: From Science to Policy in the Eastern Canadian Arctic. In Press.

Franke, A., M. Setterington, G. Court, and D. Birkholz. 2010. Long-term trends of persistent organochlorine pollutants, occupancy and reproductive success in Peregrine Falcons (*Falco peregrinus tundrius*) breeding near Rankin Inlet, Nunavut, Canada. Arctic 63:442-450.

Jean-Gagnon, F. P. Legagneux, O. P. Love, H. G. Gilchrist, S. Bélanger, J. Bêty. In press. Sea ice conditions drive breeding propensity and timing of breeding in arctic-nesting common eiders (*Somateria mollissima*). Oecologia, in press.

Jenkins, D., G. Yannic, J. Schaefer, J. Conolly, and N. Lecomte 2018. Population structure of caribou in an ice bound archipelago. Diversity and Distribution, in press.

Meltofte H., et al. 2013. Arctic Biodiversity Assessment: Report for Policy Makers. CAFF, Akureyri, Iceland.

Verhulst, S., and J.-A. Nilsson. 2008. The timing of birds' breeding seasons: a review of experiments that manipulated timing of breeding. Philosophical Transactions of the Royal Society B-Biological Sciences 363:399-410.

Yannic G, Ortego J, Pellissier L, Lecomte N, Bernatchez L, Côté SD 2017 Linking genetic and ecological differentiation in an ungulate with a circumpolar distribution. Ecography, published online.

PUBLICATIONS

Beardsell, A., Gauthier, G., Fortier, D., Therrien, J.-F., Bêty, J., 2017, Vulnerability to geomorphological hazards of an arctic cliff-nesting raptor, the rough-legged hawk, Arctic Science, 3(2): 203-219.

Berteaux, D., Casajus, N., Angerbjörn, A., Fuglei, E., 2017a, Foreword to Supplement 1: research on a polar species—the Arctic fox, Polar Research 36.

Berteaux, D., Gauthier, G., Domine, F., Ims, R.A., Lamoureux, S.F., Lévesque, E., Yoccoz, N., 2017b, Effects of changing permafrost and snow conditions on tundra wildlife: critical places and times, Arctic Science 3, 65–90.

Berteaux, D., Thierry, A.-M., Alisauskas, R., Angerbjörn, A., Buchel, E., Doronina, L., Ehrich, D., Eide, N.E., Erlandsson, R., Flagstad, Ø., Fuglei, E., Gilg, O., Goltsman, M., Henttonen, H., Ims, R.A., Killengreen, S.T., Kondratyev, A., Kruchenkova, E., Kruckenberg, H., Kulikova, O., Landa, A., Lang, J., Menyushina, I., Mikhnevich, J., Niemimaa, J., Norén, K., Ollila, T., Ovsyanikov, N., Pokrovskaya, L., Pokrovsky, I., Rodnikova, A., Roth, J.D., Sabard, B., Samelius, G., Schmidt, N.M., Sittler, B., Sokolov, A.A., Sokolova, N.A., Stickney, A., Unnsteinsdóttir, E.R., White, P.A., 2017c, Harmonizing circumpolar monitoring of Arctic fox: benefits, opportunities, challenges and recommendations, Polar Research 36, 2.

Brown, S., Gratto-Trevor, C., Porter, R., Weiser, E.L., Mizrahi, D., Bentzen, R., Boldenow, M., Clay, R., Freeman, S., Giroux, M.-A., Kwon, E., Lank, D.B., Lecomte, N., Liebezeit, J., Loverti, V., Rausch, J., Sandercock, B.K., Schulte, S., Smith, P., Taylor, A.,Winn, B., Yezerinac, S., Lanctot, R.B., 2017, Migratory connectivity of Semipalmated Sandpipers and implications for conservation, The Condor, 119: 207-224.

Chevallier, C., Gauthier, G., Berteaux, D., 2017, Age estimation of live arctic foxes *Vulpes lagopus* based on teeth condition, Wildlife Biology 1, wlb.00304.

Curk, T., McDonald, T., Zazelenchuk, D., Weidensau, S., Brinker, D., Huy, S., Smith, N., Miller, T., Robillard, A., Gauthier, G., Lecomte, N., Therrien, J.-F., 2018, Winter irruptive snowy owls in North America are not starving, Canadian Journal of Zoology, sous presse.

Dalerum, F., Dalén, L., Fröjd, C., Lecomte, N., Lindgren, Å., Meijer, T., Pecnerova, P., Angerbjörn, A., 2017, Spatial variation in Arctic hare (*Lepus arcticus*) populations around the Hall Basin, Polar Biology, 40: 2113-2118.

Elmhagen, B., Berteaux, D., Burgess, R.M., Ehrich, D., Gallant, D., Henttonen, H., Ims, R.A., Killengreen, S.T., Niemimaa, J., Norén, K., Ollila, T., Rodnikova, A., Sokolov, A.A., Sokolova, N.A., Stickney, A.A., Angerbjörn, A., 2017, Homage to Hersteinsson and Macdonald: climate warming and resource subsidies cause red fox range expansion and Arctic fox decline, Polar Research 36.

Fauteux, D., Gauthier, G., Berteaux, D., Bosson, C., Palme, R., Boonstra, R., 2017, Assessing stress in Arctic lemmings: Fecal metabolite levels reflect plasma free corticosterone levels, Physiological and Biochemical Zoology 90, 370–382.

Fauteux, D., Gauthier, G., Mazerolle, M., Coallier, N., Bêty, J., Berteaux, D., 2018, Evaluation of invasive and non-invasive methods to monitor rodent abundance in the Arctic, Ecosphere, In Press.

Fauteux, D., Gauthier, G., Slevan-Tremblay, G., Berteaux, D., 2018, Life in the fast lane: learning from the rare multi-year recaptures of brown lemmings in the High Arctic, Arctic Science, AS-2017-0017, In press.

Fauteux, D., Slevan-Tremblay, G., Gauthier, G., Berteaux, D., 2017, Feeding preference of brown lemmings (*Lemmus trimucronatus*) for plant parts of Arctic willow (*Salix arctica*), Polar Biology 40, 2329–2334.

Gendreau, Y., Lachance, A., Ricard, M., Gilbert, H., Casajus, N., Berteaux, D., 2017, Changements climatiques: défis et perspectives pour les plantes vasculaires en situation précaire au Québec, Le Naturaliste Canadien 142, 16–35.

Guery, L., S. Descamps, K. Hodges, R. Pradel, B. Moe, S. A. Hanssen, K. Erikstad, G. Gabrielsen, H. G. Gilchrist, S. Jenouvrier, and J. Bêty. Winter extra-tropical cyclones influence seabird survival: variation between and within common eider populations. Marine Ecology Progress Series. In press.

Guéry, L., Descamps, S., Pradel, R., Hanssen, S. A., Erikstad, K. E., Gabrielsen, G.W. Gilchrist, H. G., Bêty, J., 2017, Hidden survival heterogeneity of three Common eider populations in response to climate fluctuations, Journal of Animal Ecology, 86(3): 683–693, DOI: 10.1111/1365-2656.12643.

Hargan, K. E., N. Michelutti, K. Coleman, C. Grooms, J. M. Blais, L. E. Kimpe, H. G. Gilchrist, M. Mallory, and J. P. Smol. 2017. Cliff-nesting seabirds influence production and sediment chemistry of lakes situated above their colony. Science of the Total Environment 576: 85-98.

Hennin, H., Dey, C., Bety, J. Gilchrist, H.G., Legagneux, P., Williams, T.D., Love, O.P., 2018, Rate of condition gain mediates optimal combinations of lay date and clutch size: a test of the condition-dependent individual optimization model. Functional Ecology. In press.

Henri, D., F. Jean-Gagnon, and H. G. Gilchrist. Using Inuit traditional ecological knowledge to investigate Avian Cholera among common eiders in the eastern Canadian Arctic. Ecology and Society. In press.

Iverson, S. A., M. R. Forbes, M. Simard, C. Soos, and H. G. Gilchrist. Avian cholera emergence in an Arctic seabird: assessing outbreak patterns and transmission risk. Ecology and Society. In press.

Jean-Gagnon, F., Legagneux, P., Gilchrist, H.G., Bélanger, S., Love, O.P., and Bêty, J., 2018, The impact of sea ice conditions on breeding decisions is modulated by individual state in an arctic partial capital breeder, Oecologia, 186:1-10.

Jenkins, D., Yannic, G., Schaefer, J., Conolly, J., Lecomte, N., 2018, Population structure of caribou in an ice bound archipelago, Diversity and Distribution, In press.

Kristen, K., Franke, A., Lecomte, N., Bêty, J., 2018, Nesting habitat selection and distribution of an avian top predator in the Canadian Arctic, Arctic Science, In press.

Lai, S., Bêty, J., Berteaux, D., 2017, Movement tactics of a mobile predator in a meta-ecosystem with fluctuating resources: the arctic fox in the High Arctic, Oikos, 126(7):937-947, DOI : 10.1111/oik.03948.

Lai, S., Quiles, A., Lambourdière, J., Berteaux, D., Lalis, A., 2017, Fine-scale population genetic structure of arctic foxes (*Vulpes lagopus*) in the High Arctic, BMC Research Notes, 10, 663-669.

Lamarre, J.-F., Legagneux, P., Gauthier, G., Reed, E., Bêty, J., 2017, Predator-mediated negative effects of overabundant snow geese on arctic-nesting shorebirds, Ecosphere, 8(5):e01788.

Lamarre, V., Franke, A., Love, O.P., Legagneux, P., Bêty, J., 2017, Linking pre-laying energy allocation and timing of breeding in a migratory arctic raptor, Oecologia, 183:653.

Lamarre, V., P. Legagneux, A. Franke, N. Casajus, D. C. Currie, D. Berteaux, and J. Bety. Precipitation and ectoparasitism reduce reproductive success in an arctic-nesting top-predator. Scientific Reports. Accepted.

Léandri-Breton, D.-J., Jaffré, M., Bêty, J., 2018, A new dark morph in the Canadian Arctic raises questions about molting and polymorphism in Long-tailed Jaeger (*Stercorarius longicaudus*), Wilson Journal of Ornithology, 130, In Press.

Legagneux, P., Casajus, N., Cazelles, K., Chevallier, C., Chevrinais, M., Guéry, L., Jacquet, C., Jaffré, M., Naud, M.-J., Noisette, F., Ropars, P., Vissault, S., Archambault, P., Bêty, J., Berteaux, D., Gravel, D., 2018, Our house is burning: Discrepancy in climate change vs. biodiversity coverage in the media as compared to scientific literature, Frontiers in Ecology and Evolution 5, Article 175.

Mallory, C., H. G. Gilchrist, G. J. Robertson, J. F. Provencher, B. M. Braune, M. R. Forbes, and M. L. Mallory. 2017. Hepatic trace element concentrations of breeding female common eiders across a latitudinal gradient in the eastern Canadian Arctic. Marine Pollution Bulletin 124: 252-257.

Norén, K., Dalén, L., Flagstad, Ø., Berteaux, D., Wallén, J., Angerbjörn, A., 2017, Evolution, ecology and conservation—revisiting three decades of Arctic fox population genetic research, Polar Research, 36.

Peck, K., Franke, A., Lecomte, N., Bêty, J., 2018, Nesting habitat selection and distribution of an avian top predator in the Canadian Arctic, Arctic Science, In Press.

Rioux, M.-J., Lai, S., Casajus, N., Bêty, J., Berteaux, D., 2017, Winter home range fidelity and extraterritorial movements of Arctic fox pairs in the Canadian High Arctic, Polar Research, 36 (Sup1): 11.

Ripple, W.J., Wolf, C., Newsome, T.M., Galetti, M., Alamgir, M., Crist, E., Mahmoud, M.I., Laurance, W.F., and 15,364 scientist signatories from 184 countries, 2017, World scientists' warning to humanity: A second notice, BioScience 67, 1026–1028.

Robillard, A., G. Gauthier, J.F. Therrien & J. Bêty, 2018, Wintering space use and site fidelity in a nomadic species, the snowy owl, Journal of Avian Biology, condiitonal acceptance.

Robillard, A., Gauthier, G., Therrien, J.-F., Fitzgerald, G., Provencher, J. F., Bêty, J., 2017, Variability in stable isotopes of snowy owl feathers and contribution of marine resources to their winter diet, Journal of Avian Biology, 48(6): 759-769, 10.1111/jav.01257.

Robinson, B. G., A. Franke, and A. E. Derocher. 2017. Stable isotope mixing models fail to estimate the diet of an avian predator. Auk 135: 6-70.

Steenweg, R., G. Crossin, T. Kyser, F. Merkel, H. G. Gilchrist, H. Hennin, G. Robertson, J. Provencher, J. Flemming, and O. Love. 2017. Stable isotopes can be used to infer the overwintering locations of pre-breeding marine birds in the Canadian Arctic. Methods in Ecology and Evolution. Online.

Therrien, J.-F., Lecomte, N., Zgirski, T., Jaffre, M., Beardsell, A., Goodrich, L., Bêty, J., Franke, A., Zlonis E., Bildstein, K., 2017, Long-term phenological shifts in migration and breeding area residency in eastern North American raptors, Auk, 134 :871-881.

Therrien, J.-F., Weidensaul, S., Brinker, D., Huy, S., Miller, T., Jacobs, E., Weber, D., McDonald, T., Lanzone, M., Smith, N., Lecomte, N., 2017, Winter use of a highly diverse suite of habitats by irruptive snowy owls, Northeastern Naturalist, 24: B81-B89.

Weiser, A.L., Lanctot, R.B., Brown, S.C., Gates, H.R., Bentzen, R.L., Bêty, J. & 16 co-authors, 2018, Environmental and ecological conditions at Arctic breeding sites have limited effects on true survival rates of adult shorebirds, Auk, 135:29-43.

Weiser, E.L., Brown, S.C., Lanctot, R.B., Gates, H.R., Abraham, K., Bentzen, R.L., Bêty, J., Boldenow, M.L., Brook, R., Donnelly, T.F., English, W.B., Flemming, S.A., Franks, S.E., Gilchrist, H.G., Giroux, M.-A., Johnson, A., Kendall, S. Kennedy, L.V., Koloski, L., Kwon, E., Lamarre, J.-F., Lank, D.B., Latty, C.J., Lecomte, N. & 14 co-authors, 2018, Effects of environmental conditions on reproductive effort and nest success of Arctic-breeding shorebirds, Ibis, DOI: 10.1111/ibi.12571.

Weiser, E.L., Brown, S.C., Lanctot, R.B., Gates, H.R., Abraham, K., Bentzen, R.L., Bêty, J., Boldenow, M.L., Brook, R., Donnelly, T.F., English, W.B., Flemming, S.A., Franks, S.E., Gilchrist, H.G., Giroux, M.-A., Johnson, A., Kennedy, L.V., Koloski, L., Kwon, E., Lamarre, J.-F., Lank, D.B., Lecomte, N. & 14 co-authors, 2017, Life-history tradeoffs revealed by seasonal declines in reproductive traits of Arctic-breeding shorebirds, Journal Avian Biology, Accepted October 2017. doi: 10.1111/jav.01531.

Weiser, E.L., Brown, S.C., Lanctot, R.B., Gates, H.R., Abraham, K.F., Bentzen, R.L., Bêty, J., Boldenow, M.L., Brook, R.W., Donnelly, T.F., English, W.B., Flemming, S.A., Franks, S.E., Gilchrist, H.G., Giroux, M.-A., Johnson, A., Kendall, S., Kennedy, L.V., Koloski, L., Kwon, E., Lamarre, J.-F., Lank, D.B., Latty, C.J., Lecomte, N., Liebezeit, J.R., McKinnon, L., Nol, E., Perz, J., Rausch, J., Robards, M., Saalfeld, S.T., Senner, N.R., Smith, P.A., Soloviev, M., Solovyeva, D., Ward, D.H., Woodard, P.F., Sandercock, B.K., 2018, Effects of environmental conditions on reproductive effort and nest success of Arctic-breeding shorebirds, Ibis, publié en ligne, doi.org/10.1111/ibi.12571.

Yannic, G., Ortego, J., Pellissier, L., Lecomte, N., Bernatchez, L., Côté, S.D., 2017, Linking genetic and ecological differentiation in an ungulate with a circumpolar distribution, Ecography, doi.org/10.1111/ecog.02995.

Yannic, G., Statham, M.J., Denoyelle, L. , Szor, G., Sacks, B.N., Lecomte N., 2017, Investigating the ancestry of putative hybrids: a study case in the area of overlap between arctic and red foxes, Polar Biology, 40: 2055-2062.

WATER SECURITY AND QUALITY IN A CHANGING ARCTIC

Project Team

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ABSTRACT

Water is crucial to Northerners and plays a vital role in the stability of landscapes and ecosystems. Projected climate changes are anticipated to substantially impact aquatic and terrestrial ecosystems, and this project uses an integrated watershed approach to identify how climate and permafrost change drive freshwater quality and availability. This comprehensive research program is focused on understanding changing water systems through climate and permafrost change, and integrating this with the terrestrial ecosystem. Research is conducted primarily at the Cape Bounty Arctic Watershed Observatory (CBAWO) to provide key insights into drivers of water quality and quantity changes that are relevant for Northerners. This knowledge is also being transferred to build sustainable research capacity with stakeholders through a collaborative research program in the Apex River near Iqaluit, NU. The sustainable monitoring program with stakeholders will be expanded, and training and knowledge sharing opportunities will be offered. This research is especially motivated by concerns about changes to river flow and water quality by local decision makers and residents.

KEY MESSAGES

Cape Bounty

- River flow and water quality are strongly linked to climate variability and permafrost change.
- Deep permafrost thaw on land can result in rapid downstream changes in large water bodies, with measurable impacts on the food web and fish.
- Active layer detachments brought on by permafrost thawing alters water quality and dissolved organic matter (DOM) biogeochemistry.
- Subsurface water inputs, with elevated dissolved ion concentrations, may increase DOM lability in ponds and surface runoff.
- Thermal perturbations (deep thaw) enhances the export of total dissolved solids including dissolved inorganic nitrogen (DIN) from High Arctic environments.
- Water column concentrations of total mercury (THg) were consistently higher (~3-fold) in permafrost impacted West Lake than in unimpacted East Lake over the period 2007-2016, while toxic methyl Hg concentrations were extremely low (0.01 ng/L) and comparable in the two lakes.
- Mercury, cesium and rubidium concentrations in landlocked char have increased significantly in West Lake while declining in East Lake over the period 2008-2017.
- Average concentrations of pCO_2 and pCH_4 in West Lake (74.1 umol/L and 0.024 umol/L, respectively) were lower than in East Lake (77.5 umol/L and 0.172 umol/L, respectively), but all concentrations were well above atmospheric equilibrium, suggesting that these two lakes are sources of these two greenhouse gases to the atmosphere.
- Variation in soil nitrogen availability in wet-sedge meadows at CBAWO has a positive impact on plant growth, and leads to enhanced net carbon uptake from the atmosphere.
- Potential climate-induced changes in soil nitrogen availability in High Arctic wetlands will enhance carbon dioxide removal from the atmosphere and help reduce the impact of warming on atmospheric carbon dioxide concentration (a negative feedback).
- 2017 marks the 8th season of energy and CO_2 flux measurements at Cape Bounty. This is a unique and incredibly valuable dataset being used to better understand the dynamic range of tundra function and carbon dynamics in summer.
- We have demonstrated (using satellite spectral indices) that the vegetation abundance at the Cape Bounty Arctic Watershed Observatory (CBAWO) has increased over the last 30 years. However, this change is not uniform and varies based on specific vegetation types.

Niaqunguk (Apex) River

- We completed a 4th season of end-of-winter snow surveying in the Apex River watershed in collaboration with Nunavut Arctic College-Environmental Technology Program (NAC-ETP) students.
- Using snow survey and stream discharge measurements in combination with the first season of energy and CO_2 flux measurements in the Apex River watershed, we can quantify the water budgets and the factors that influence delivery to downstream water bodies.
- The preferential thawing of the active layer is an important control on hillslope drainage dynamics in permafrost environments.
- Forthcoming results from field studies conducting during the summer of 2017 will greatly advance our understanding of the factors controlling the storage and routing of surface runoff and shallow groundwater within the Apex River watershed.

- Forthcoming results from analysis the recently completed five season hydrochemical data set (including DOC, DON, major ions, water stable isotopes, and dissolved metals) in combination with the river discharge measurements, will be used to examine how variations in inter-annual and seasonal hydroclimatic conditions influence the water volumes, flow routing and water quality in the Apex River watershed.

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 Niaqunguk (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 2017, our objectives were:

Cape Bounty

1. Continue to determine the hydrological impacts of changing climate and permafrost in High Arctic rivers and lakes.
2. Determine the extent of active layer detachment impact on water quality and dissolved organic matter biogeochemistry and biodegradability.
3. Determine the long term response (2003-2016) of dissolved inorganic nitrogen (DIN) to physical disturbance and thermal perturbation in paired High Arctic catchments.
4. Determine tributary inputs and lake water concentrations of mercury and methyl mercury to West and East Lake at Cape Bounty as part of an assessment of mercury biogeochemistry at Cape Bounty.

5. To 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.
6. Determine levels of 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.
7. Investigate levels and trends of persistent organic pollutants (POPs) in char and in waters of East and West Lake and tributaries [added in 2015 with support from NCP].
8. Quantify seasonal and interannual variability in fluxes of water and CO_2 between the tundra and the atmosphere as well as the factors that influence them.
9. Quantify controls on spatial and temporal variability in soil nitrogen availability in a wet-sedge meadow.
10. Explore the impact of variation in soil nitrogen availability on the net carbon balance of wet-sedge meadows.
11. Develop efficient methods for estimating vegetation cover fraction and absorbed photosynthetically active radiation (fAPAR) at multiple scales using remote sensing data.
12. Examine the spatial and temporal patterns of biophysical variables across a latitudinal gradient (and over time) in the Canadian Arctic; and to determine terrain controls over landscape stability for developing landscape-scale permafrost susceptibility models.

Niaqunguk (Apex) River

1. To develop a surveying protocol for accurate quantification of basin wide end-of-winter snow water equivalent in the Apex River watershed and to produce a long-term record of its inter-annual variability with long-term monitoring.
2. Advance our understanding of the dominant physical controls governing the routing of shallow groundwater from hillslopes to streams in the Niaqunguk (Apex) River.
3. Determine the spatiotemporal evolution of the critical source areas that sustain baseflow during the Arctic summer.
4. Determine the key hydroclimatic controls on seasonal and inter-annual variability in solute, carbon and nutrient loads in streams and lakes in the Niaqunguk (Apex) river watershed.
5. Estimate snow sublimation and terrestrial evapotranspiration fluxes for Iqaluit-area tundra ecosystems.
6. Quantify seasonal and interannual variability in fluxes of water and CO_2 between the tundra and the atmosphere as well as the factors that influence them.
7. Determine how seasonal and inter-annual variations in hydroclimatic conditions control the fluxes of dissolved organic and inorganic solutes in the Apex River.
8. Continue to deliver local training related to water quality, to increase research capacity and expertise Nunavut residents.

KNOWLEDGE MOBILIZATION

The research team has continued to deliver a high level of research publication in the scientific literature. In addition, we have undertaken diverse efforts to transfer knowledge from our research to northern stakeholders, and other interested parties.

These include:

- Maintained social media outreach with a blog http://cbawo.blogspot and CBAWO Facebook page. We are starting to get residents (Resolute, Sachs Harbour) commenting on Facebook posts, which seems to be more effective as a communication tool. We will continue to develop these social media outlets for sharing knowledge.

- Results were communicated to the Resolute Hamlet and HTA (the nearest community) and to northerners and researchers attending the annual Northern Contaminants Program results workshops (2013, 2015 and 2017).
- Results presented annually at the ArcticNet ASM as posters or oral presentations.
- Results presented to international audiences (e.g., SETAC November, 2017, Asian Permafrost Conference, July 2017).
- Results are disseminated to the scientific community and to northern stakeholders at Arctic Change 2017, the ArcticNet Annual Scientific Meeting, the annual Canadian Geophysical Union meeting, and also at CAGONT, the Ontario meeting of the Canadian Association of Geographers, among others.
- N. Scott testified at a Senate Committee hearing on Climate Change impacts on Forestry and Agriculture.
- Visited students and teachers at the Qarmartalik School in Resolute Bay, NU, and judged the local science fair in June 2017 (four team members).
- S. Lamoureux visited Qarmartalik School in February 2018 for presentation and initiation of summer employment opportunities for students.
- Numerous manuscripts prepared and submitted to scientific journals.
- Dr. Treitz was a visiting professor at the Arctic Research Centre at the University of Umea (ARCUM) in Sweden. While there, he interacted with researchers at the ARCUM and gave a public lecture on his research funded by ArcticNet. While in Sweden, he was also invited to give presentations at the KTH Royal Institute of Technology in Stockholm and at the University of Lund.
- Dr. Melissa Lafrenière has given public lectures at the Université Catholique du Louvain, in Belgium, and at l´École Nationale Supérieure Agronomique de Toulouse in France, while on sabbatical in Europe, highlighting the research and discoveries from the network activities at the CBAWO.
- Dr. Scott Lamoureux presented lecture and provided informal interaction with Department of National Defense, Natural Resources Canada, Environment and Climate Change, Privy Council and other senior leadership during February visit to Resolute.

INTRODUCTION

Water security remains an important challenge for Arctic communities and organizations. A wide range of projected climate, permafrost and ecosystem changes are likely to affect water quantity and quality but our ability to predict these changes remain limited. The volume and quality of surface water runoff (rivers) is directly tied to the source of the water and the pathway it travels from source to stream. In permafrost catchments, climate exerts a direct control over the type, seasonality and intensity of precipitation and the thermal properties and stability of the ground. Therefore, climate change will inevitably influence both the sources (i.e. snow, rain, subsurface water, or ground ice) and the hydrological pathways (e.g. depth and rates of infiltration and subsurface flow (Lamoureux et al., 2014; Lafrenière and Lamoureux, 2013; Louiseize et al., 2014). However, there is still only a limited understanding of the processes driving water quality changes (e.g. nutrient, carbon and contaminant loads), or water sources (e.g. groundwater, rainfall) and pathways in Arctic watersheds. There is a great need to understand how changes in climate and permafrost drive changes in water quantity and quality in Arctic watersheds, and their impacts on Arctic aquatic ecosystems and northern communities. Further, there is a critical lack of capacity to undertake hydrological and terrestrial research in northern communities and building northern capacity to contribute and benefit from research remains underdeveloped.

This project represents a multi-disciplinary effort to develop key scientific knowledge about Arctic watersheds and related ecosystem processes. We are also focused on transferring our knowledge to northern communities, through collaboration and capacity building in Iqaluit through a growing research program on the Niaqunquk (Apex) River. This river has special importance to the community due to frequent use by residents, and is of critical importance as a supplemental water supply for the city to support future growth.

ACTIVITIES

In 2017, 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 International Tundra Experiment (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 1 PDF, 4 PhD, 5 MSc and 1 BScH student working in the field and on data analysis. This work was carried out from mid-May until mid-August and represented one of our most intensive hydrological monitoring efforts to date (and arguably, ever carried out in the Canadian High Arctic).

Surface water DOM and biogeochemistry

To determine if the composition and biodegradability of DOM were affected by active layer detachments we sampled water from ponds that were within ALD disturbances and ponds that were not impacted. To examine the chemical differences between river and pond waters, 14 river and 6 pond sites were collected in summer 2014 and 2015 from the West River catchment at CBAWO. The 14 river sites included: 7 main channel sites and 7 sites at first-order tributary streams. There were two tributary stream sites and 2 ponds that were significantly disturbed by active layer detachments (ALDs). The concentrations of dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) were quantified.

To determine impacts of disturbance and subsurface water inputs on the lability of DOM, water was collected from six shallow ponds in the West River watershed in early to mid-July and again in early August. The ponds were located in varying geomorphic settings, including two in active layer disturbances that formed in 2007. Samples were incubated for 28 days at 20°C in the dark, and triplicate aliquots were removed at 0, 2 7, 14 and 28 days for chemical and optical (fluorescence-absorbance) analyses.

To investigate the impact of changing climate and permafrost conditions on the fluvial nitrogen fluxes in Arctic watersheds, the long-term DIN fluxes in the West and East rivers at CBAWO were determined using the streamflow discharge and dissolve inorganic nitrogen (nitrate, and ammonium) concentrations determined for both rivers from 2003-2016. The concentrations and fluxes of DIN were then evaluated in the context of changes in thaw depth, and runoff contributions from snowmelt, baseflow and rainfall.

Lake biogeochemistry and contaminants

Surface dissolved greenhouse samples were collected from both lakes to calculate the net exchange of these greenhouse gases with the atmosphere. We also did depth profiles of these greenhouse gases in both East and West lakes to determine zones of production or consumption.

The 2017 mercury research, focussed again on collection and analysis of water from East and West Lake and their inflows, and included the analysis of unfiltered and filtered total mercury (THg) and methyl mercury (MeHg), as well as collection of arctic char. Water (0.5 L) was collected in each lake and in tributaries and large volume sampling (~200 L) water for the determination of POPs as well as for perfluorinated alkyl substances (PFASs) in June and August. Landlocked arctic char were collected in early August 2017 by team members Barst, Pope and Iqaluk. Water extracts were analysed by Marie Curie Fellow, Ana Cabrerizo, to assess trends of THg and POPs in fish over time while considering important covariates such as length, $\delta^{15}N$ and lipid content as well as fish condition factor (CF = weight x 100/length^3).

Terrestrial vegetation and soil systems

Much of the terrestrial ecosystem research in 2017 focused on quantifying spatial patterns of soil nitrogen availability in a wet-sedge meadow at CBAWO. These meadows are the most active across the landscape in terms of greenhouse gas exchange, so any changes in carbon cycling processes in these communities will have a significant impact on landscape-scale greenhouse gas exchange. Jackie Hung (new PhD student) set out to quantify interactions between soil nutrient cycles and carbon exchange between the land and the atmosphere. Resin strips (Figure 1) were used to assess spatial patterns across this large meadow, and were deployed to explore differences in soil nutrient availability across wet and dry parts of the meadow. Samples were collected over three time periods to assess temporal changes in soil nutrient availability. At the same time, static chambers (Figure 1, right) were used to quantify net ecosystem productivity, ecosystem respiration, and gross ecosystem production at the same locations. Kriging techniques were used to extrapolate patterns of soil nutrient availability across the landscape.

A wide range of biophysical and related remote sensing work was undertaken as part of the research team activities. Valerie Freemantle (MSc candidate) conducted a time series analysis of high spatial resolution satellite data (i.e., IKONOS, GeoEye, WorldView) to examine environmental change that has occurred at the CBAWO since 2003. She is currently analyzing her field measurements in the context of the satellite data. This work was extended with Mitchell Bonney (MSc, co-supervised with Dr. Ryan Danby) that examined vegetation change across the boreal forest – tundra ecotone in central Canada. He analysed intermediate spatial resolution remote sensing data (i.e., Landsat) NDVI time series to identify areas along this transect that have demonstrated change (primarily increased vegetation growth) since 1984. This research is currently in review for Remote Sensing of Environment.

Dr. Ashley Rudy (PhD 2016) published the last of her PhD manuscripts that examined fine scale subsidence/uplift using differential interferometric synthetic aperture radar (DInSAR). This DInSAR research was conducted in collaboration with Naomi Short and

Figure 1. Resin strips marked with flagging tape, and static chamber (right) for CO_2 measurements.

Brian Brisco of Natural Resources Canada (Canada Centre for Mapping and Earth Observation). In total, she produced four refereed journal articles from her PhD research using remote sensing data to examine permafrost degradation.

Chen Shang (PhD candidate) completed a SAR analysis for modelling soil moisture at two sites on Melville Island (i.e., CBAWO and Sabine Peninsula). The results of this research are currently in review in a special issue focused on soil moisture estimation and applications in Advances in Meteorology.

Niaqunquk (Apex) River

We carried out our fifth successful field season investigating water issues in the Apex River in close collaboration with the Nunavut Research Institute. In collaboration with NAC ETP students, Dr. Richardson's team conducted extensive snow surveys across the Apex River watershed for the 2017 field season. An example showing 2015 and 2016 surveys is shown in Figure 2. These surveys involve snow depth and density sampling along multiple 10 km transects using stratified random sampling. This work has extended the Apex River snow record to 4 years.

Field work activities for the hillslope scale subsurface flow study was completed during the summer of 2016, and is the subject of the manuscript by Chiasson-Poirier et al. that was submitted to the journal Water Resources Research in December 2017.

During the summer of 2017 we conducted field studies in the Apex River watershed to determine the spatiotemporal dynamics of the critical source areas of groundwater that sustain baseflow to the river during the Arctic summer. This work was conducted by Gabriel Chiasson-Poirier (MSc student) and Marco Goudreault (BSc student) under the supervision of Jan Franssen (Université de Montreal). A network of 27 temporary hydrometric stations were installed throughout the river network to provide a distributed and continuous record of streamflow from headwater tributaries (12) and along reaches of the main reaches of the river network. Additionally, these 27 monitoring sites were measured twice weekly (between June 19th and July 31st) for electrical conductivity and pH (measured in situ), with water samples collected for analysis of natural groundwater tracers (i.e., Dissolved Organic Carbon, Total Dissolved Nitrogen, Oxygen and Hydrogen Isotopes). These samples are in the process of being analyzed at the Facility for Biogeochemical Research on Environmental Change and the Cryosphere (Melissa Lafrenière). To our knowledge this data collected during the summer of 2017 provides a globally unique watershed scale high spatiotemporal resolution dataset of paired hydrometric and geochemical measurements.
Over the 2017 field season we also continued our investigation of the catchment scale response of water flow and water quality to inter-annual and seasonal variations in hydroclimatic conditions, which included river discharge measurements and the collection of water samples for analyses of dissolved organic matter, dissolved inorganic ions, and trace metals. Due to several laboratory instrument failures and malfunctions, the analysis of this unique multi-year water quality data (2013-2017) set has only just been completed in recent months. We anticipate the analyses of this will occur this summer and fall, with publications arising from this work over the fall of 2018 and winter 2019. We expect that that these datasets will generate important discoveries regarding the evolution of source water contributions to Arctic river systems. Fundamental understanding that is urgently need to understand how the quantity and quality of streamflow in arctic rivers systems is likely to respond to climate change.

In June 2017, a new Eddy Covariance system (Campbell Scientific EC150 open-path IRGA and CSAT3B 3-D sonic anemometer) system was installed on our meteorological station in the Apex River watershed. From mid-June to mid-September, the system was used to estimate total evapotranspiration and CO_2 gas exchange.

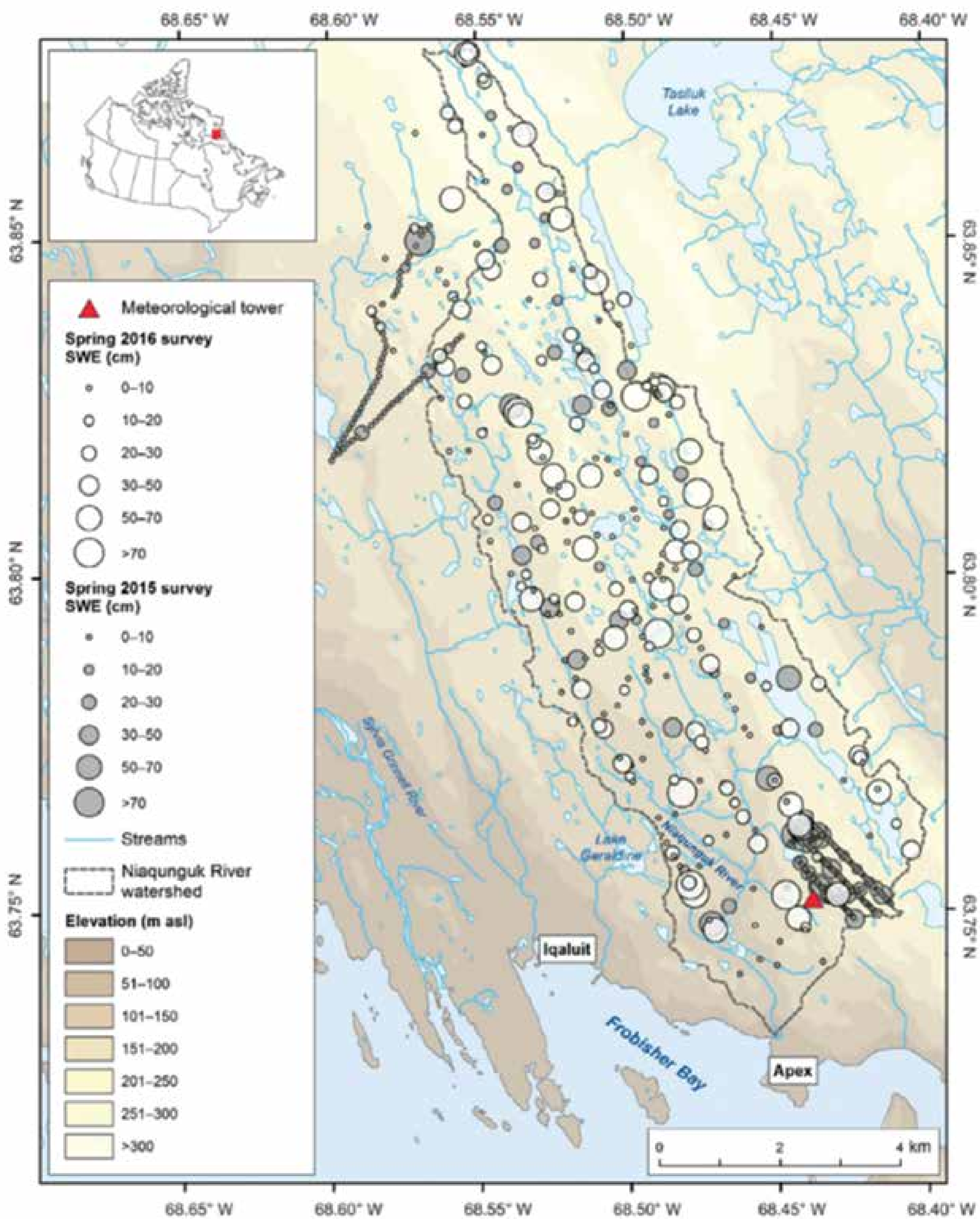

Figure 2. Map of 2015 and 2016 snow survey locations and results. The annual survey is conducted along four to six 10-km skidoo transects.

Figure 3. From left to right: Sonja (instructor), Jason, Garrett, Mary, Billie-Jean and Mesha (instructor).

The Analytical Services Unit (ASU) at Queens University has maintained on-site and off-site training programs since the 1990's. Iqaluit Analytical Services Unit (IASU) a satellite operation of ASU has offered the Environmental Sampling and Analysis Training program since 2010. Courses of this nature were started while ASU was involved with the DEW-line clean-up at Resolution Island and the programs then as now were intended for Inuit and other residents of Nunavut. The course is largely a practical one aimed at increasing awareness, understanding and problem solving techniques for environmental issues facing the Arctic community. The current course is focused on monitoring, analyzing and remediating contaminants in the Arctic. The program curricula include but is not limited to: environmental sampling, general laboratory methods, and laboratory quality assurance, primary measurements of mass and volume, specific methods to measure contaminants, laboratory quality control, calibration of instruments, laboratory housekeeping.

Figure 4. The 2017 trainees from left to right: Nysana Jr Qillaq, Jason Harasimo, Mary Omole, Garret Jessup and Billie-Jean Eetuk.

As the focus is mostly a practical one the course represents something of a reversal in format from usual academic offerings: field sampling trips and hands on laboratory sessions are supplemented by lectures depending mostly on the students' interests. Lectures presented this year included: basic chemistry, environmental chemistry, laboratory accreditation to the ISO 17025 standard (often a regulatory requirement), environmental problem solving, site remediation including the Resolution Island case study, and metals and hydrocarbon contaminants analysis.

The techniques and approaches used to address environmental contaminants help prepare trainees for possible employment, for monitoring the environment in which they live, and for resolving future environmental issues. The 2017 students were Mary Omole, Billie-Jean Eetuk, Jason Harasimo, Garret Jessup and for the first week of the course Nysana Jr Qillaq also participated; Nysana enrolled in the ETP Program (Arctic College) in September 2017.

RESULTS

Cape Bounty

Surface water DOM and biogeochemistry

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 6 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; mean±SD) 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 $\Delta^{14}C$ and $\delta^{13}C$ values ($P<0.05$). The $\Delta^{14}C$ 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

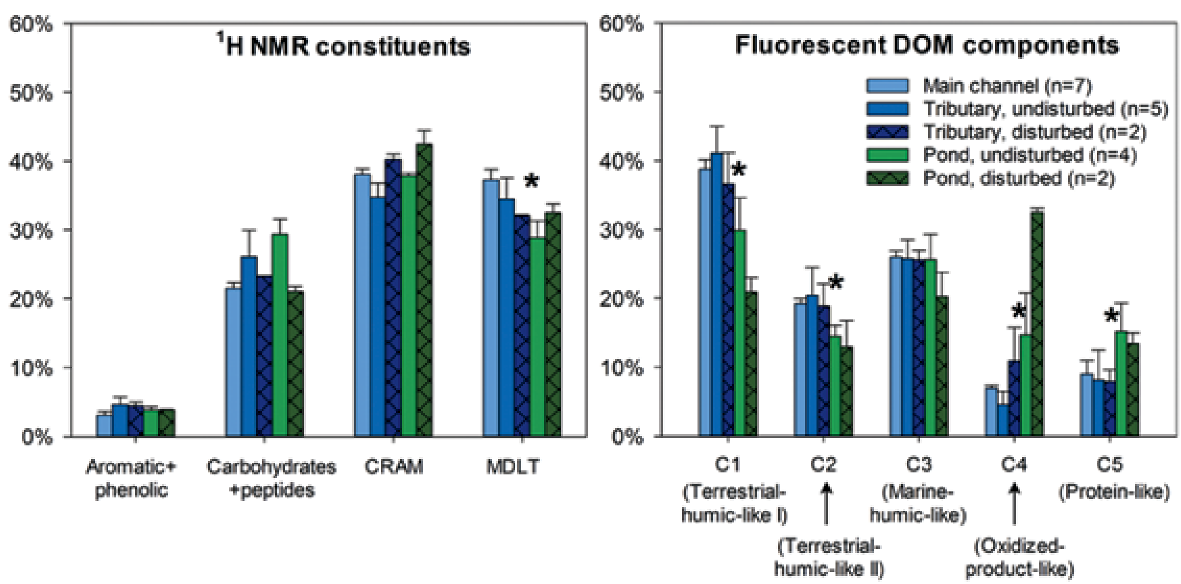

*Figure 5. Different spectroscopic characteristics (mean±SD) of river and pond dissolved organic matter from West River catchment of Cape Bounty Arctic Watershed Observatory. *Significant differences between river and pond. From Wang et al. 2018. © 2018 American Chemical Society.*

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 5). Compared to the ^{1}H NMR spectra, the diffusion edited ^{1}H NMR showed an increase in the percentage of carbohydrates+peptides and decreases in the percentages of the MDLT and CRAM constituents in all samples. For the absorbance and fluorescence-associated indices, the pond water had significantly higher E2/E3 ratio and BIX but significantly lower SUVA and HIX ($P<0.05$). Fluorescence PARAFAC divided the emission excitation matrices into five components: 1) terrestrial-humic-like I, 2) terrestrial-humic-like II, 3) marine-humic-like, 4) oxidized-product-like, and 5) protein-like. Compared to the river samples, the pond samples showed significantly lower abundances of terrestrial-humic-like I and II 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, $\delta^{13}C$, and the relative abundance of

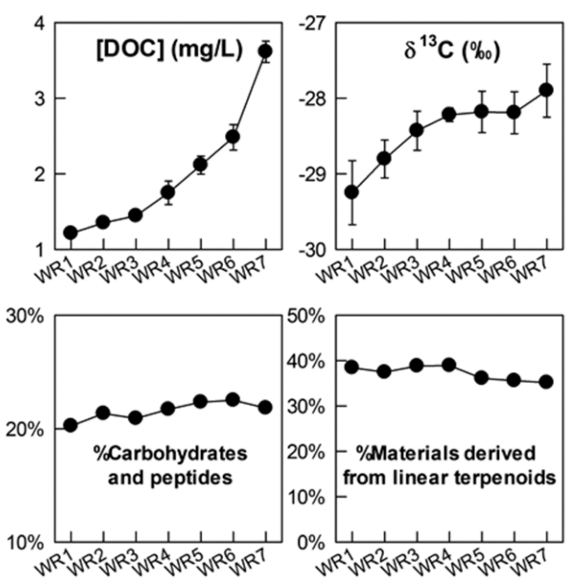

Figure 6. Increasing autochthonous contribution in river dissolved organic matter (DOM) from upper to lower stream of the West River. From Wang et al. 2018. © 2018 American Chemical Society.

carbohydrate+peptides in ^{1}H NMR increased, and the relative abundance of MDLT in ^{1}H NMR slightly decreased (Figure 6). Comparing the ALD-disturbed and disturbed tributary and pond samples, the ALD-disturbed DOM had much less carbohydrates+peptides but more CRAM constituents in the ^{1}H NMR spectra. Also, they had significantly less terrestrial-humic-like I fluorescent components but more oxidized-product-like fluorescent components. Particularly, ALD-disturbed ponds showed higher $\Delta^{14}C$ and lower DOC concentrations than other ponds (Wang et al., 2018).

Seasonal DIN fluxes in the West River varied substantially over the period of investigation. Nitrate typically dominated the DIN flux, and the patterns in nitrate concentrations were similar to those for the other dissolved inorganic ions, as indicated by the TDS flux (Figure 7). The highest DIN fluxes occurred in 2008 (the year immediately following the permafrost disturbance in this catchment) and in 2012 and 2016, which were warm summers that included substantial DIN contributions from baseflow and stormflow runoff.

Lake biogeochemistry and contaminants

Strong seasonal relationships (r^2 =0.49-0.94) between East and West river THg concentration and suspended sediment concentration (SSC) were observed throughout 2007-2017 allowing for high temporal resolution THg concentration estimates based on more detailed SSC records. River Hg flux calculated using THg-SSC rating curves show large inter-annual variability from both river catchments. Although East and West catchments are morphologically similar, they display subtle physiographic differences that influence river runoff. To account for these differences, specific THg fluxes are normalized for catchment area and total runoff. Specific THg fluxes show almost identical inter-annual trends in both watersheds, except immediately following disturbance and in years with substantial stormflow contributions (Figure 8). We therefore hypothesize that increased sediment availability in the West River resulting from widespread, localized permafrost disturbances in 2007, led to increased 2008

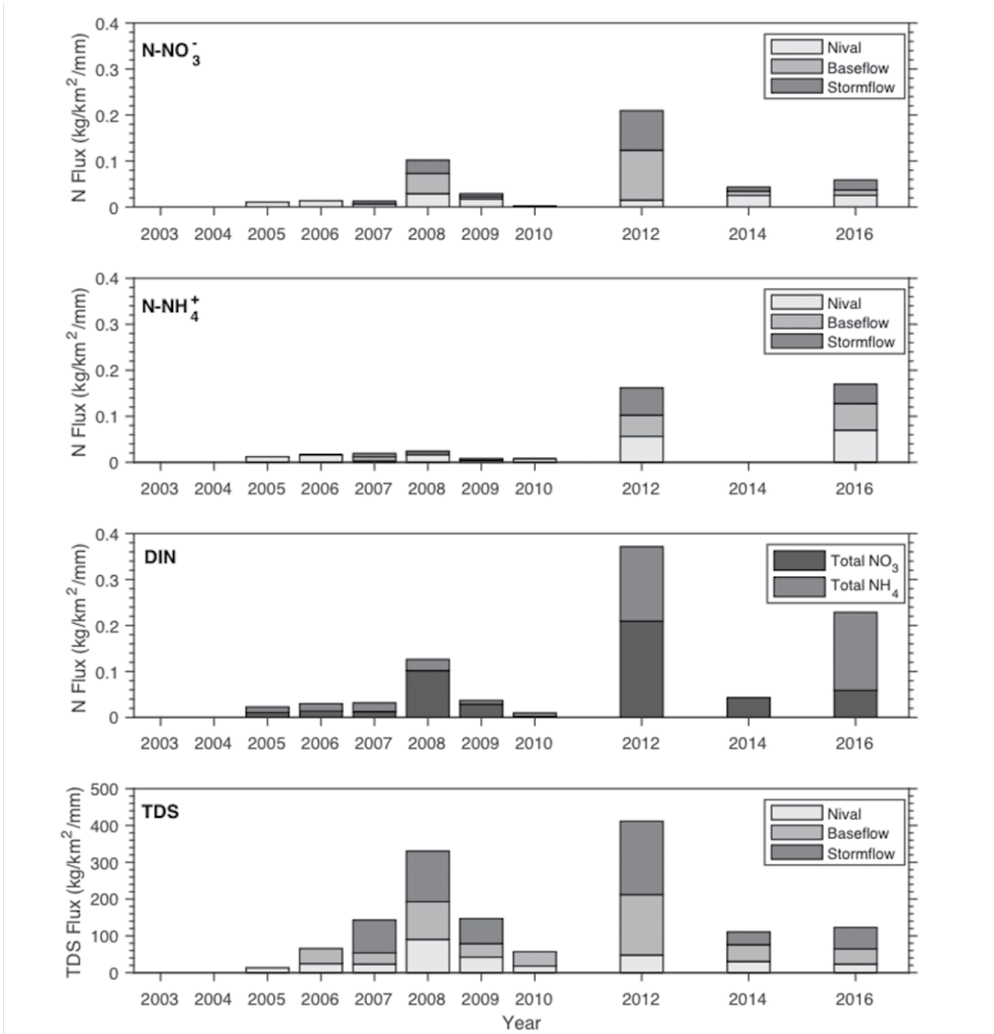

Figure 7. West River seasonal fluxes of N-NO$_3^-$, N-NH$_4^+$, and TDS divided into nival, baseflow, and stormflow periods. Total N-NO$_3^-$ and N-NH$_4^+$ were summed to calculate DIN total. Samples were not collected in 2011, 2013, and 2015. Note the increase of N-NO$_3^-$ and TDS fluxes in 2008, and the peak of N-NO$_3^-$, N-NH$_4^+$, and TDS in 2012.

specific THg flux. The timing and intensity of runoff is an important driver of THg fluxes in this system. The nival period normally dominates the flow regime in the High Arctic but due to bed armouring, the river channel contributes proportionally less THg during snow melt than rainfall runoff (Figure 8). For example, in 2009 both rivers experienced two successive late-season rainfall events, transferring ~63% and 51% of the total seasonal THg flux from the East and West catchment, respectively.

Lake water column concentrations of THg and MeHg were reviewed and summarized during 2016. 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. 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.

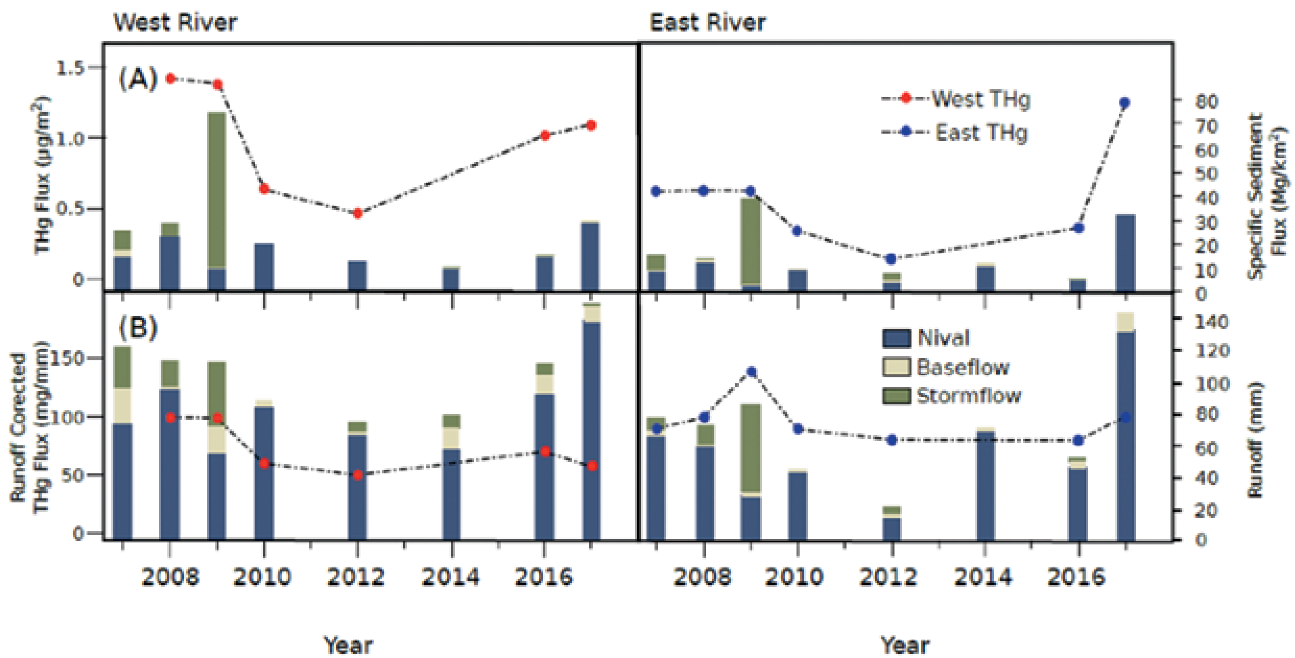

Figure 8. Summary of THg flux, runoff and specific sediment flux for each hydrological period in East and West Rivers from 2007 to 2017. A) THg flux by area over the Specific Sediment flux. B) runoff corrected THg flux and seasonal runoff contributions.

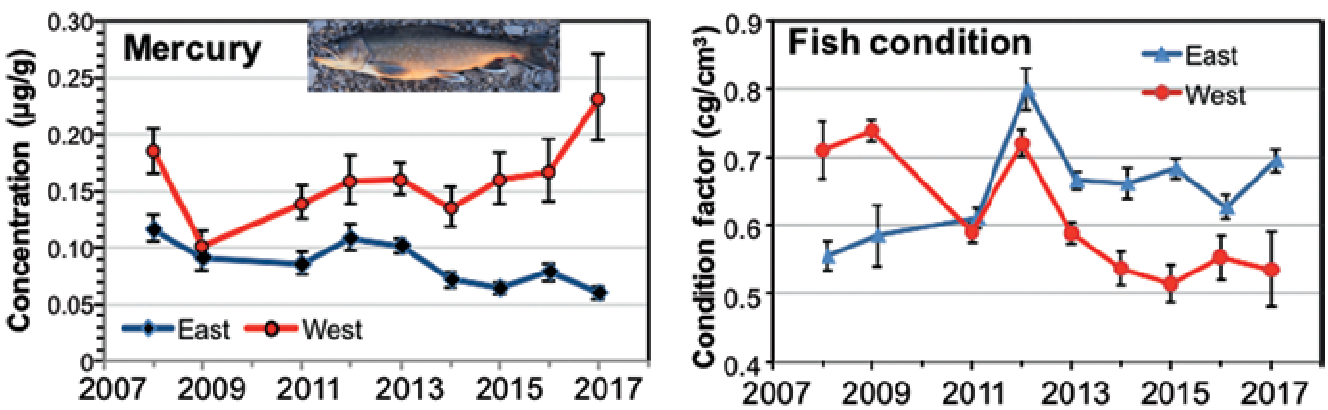

Figure 9. Trends in concentrations of mercury and fish condition in landlocked char from East and West Lakes. Symbols and vertical bars for mercury represent length adjusted geometric means and standard errors. Symbols for condition factor represent arithmetic means and standard errors.

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 (Figure 9). THg in char muscle is mainly (>90%) in the form of MeHg. Mercury has increased in char from West Lake (7.3%/yr) while declining in East Lake (-5.9%/yr). Cesium increased significantly in char from West Lake (4.8%/yr) and declined significantly in East Lake (-7.5%/yr). Rubidium and thallium did not increase in West Lake (1.2 and -1.5%/yr) but declined significantly in East Lake (-5.1 and -8.4%/yr) while selenium showed no time trend but has been consistently higher in East Lake char unlike most other elements. Arsenic, potassium, and zinc were present at similar concentrations in char in both lakes throughout the study period with no clear time trends.

Additionally, PCBs were detected in water from both lakes, in a range of 16-33 pg/L (sum of 71 PCB congeners), before melting (June 2016). Larger concentrations were detected in the lakes after the melting period (August 2016), of 200-223 pg/L. A similar pattern was observed in the tributaries. This suggests an important influx of PCBs from snow melting to lakes and tributaries.

Significantly increasing trends of total PCBs (+2.1%/yr) and DDT (+1.3%/yr) but not PFASs or hexachlorocyclohexanes (HCHs) over the period 2008 to 2016 were observed in char from West Lake. The time series (2008-2015) suggests that total PFASs in char are decreasing at a rate of 31%/y in West Lake and 22%/y in East Lake. The increases of PCBs and DDT in char from West Lake were associated with increases on lake turbidity during the same time period. Finally, CF and % lipid content in the char have declined significantly in West Lake at 3.9%/yr with lowest values associated with high turbidity (2013-15). No significant change in CF has been found for char in East Lake.

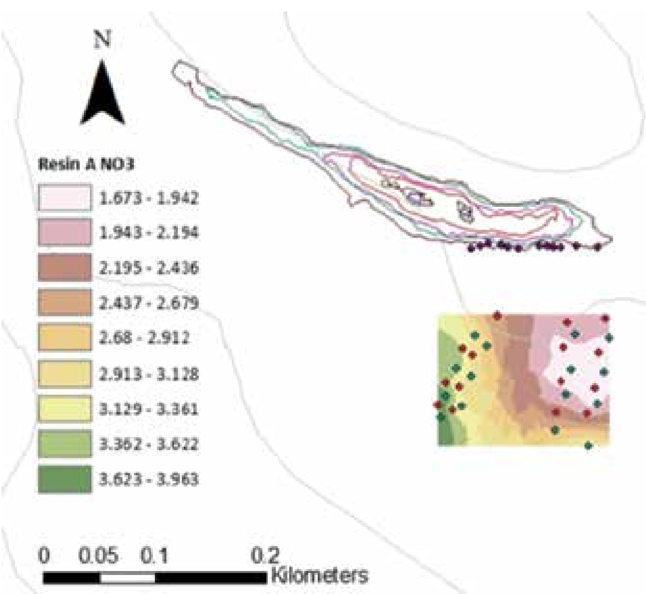

Figure 10. Spatial patterns of soil nitrate concentrations. Large square is the experimental plot area at base of snowfield (contours). Points are sampling locations. Dry strips are green symbols, wet strips are red symbols.

Terrestrial vegetation and soil systems

Soil nitrate levels differed markedly across the wet-sedge meadow site, although not in the direction expected. While we anticipated a change in concentrations as one moved away from the permanent snowfield, we found that the largest variation occurred in an E/W direction instead of N/S (Figure 10). The highest nitrate concentrations were located on the W side of the plot, and extended significantly away from the snowfield. There was variation in soil nitrate as you moved N to S, with higher concentrations of soil nitrate located the furthest from the snowfield. Wet tracks had higher concentrations of nitrate compared to the drier tracks. These results highlight the complex interactions between soil temperature, moisture, and nutrient concentration in wet-sedge meadows.

While environmental variables such as soil moisture explain well over 50% of the variation in carbon exchange rates, adding soil nitrate concentration to the regression model led to a significant improvement in our ability to predict carbon dioxide exchange with the atmosphere. Adding soil nitrate concentrations increased prediction of gross ecosystem production by about 5% (Figure 11, top), while doing the same comparison but for ecosystem respiration showed no difference when soil nitrate was added to the model. Gross ecosystem productivity was most influenced by variation in soil nitrate – this is not too surprising, since photosynthesis is more heavily affected by soil nitrate levels than is soil respiration, carried out by microorganisms.

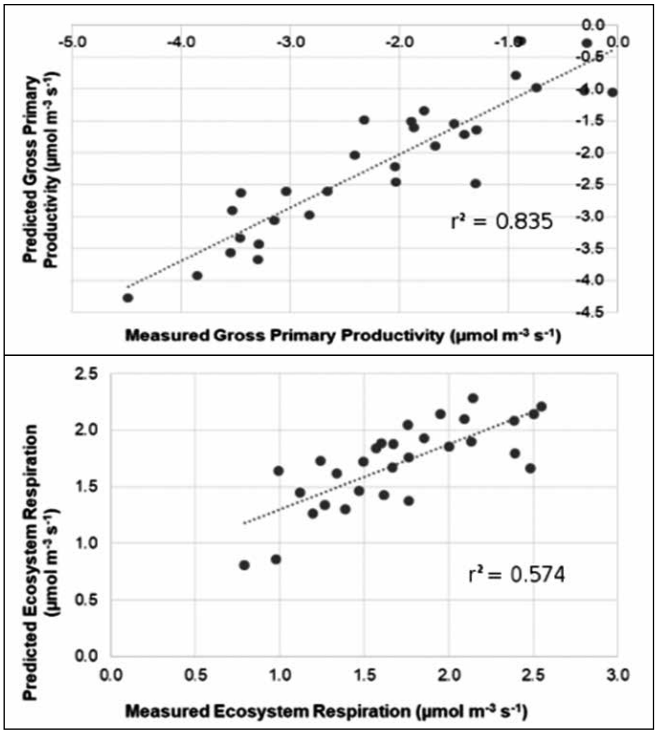

Figure 11. Relationship between measured gross ecosystem productivity (top) and modeled gross ecosystem productivity including nitrogen in the model. Relationship for ecosystem respiration shown on the bottom.

Widespread increases in the productivity of northern tundra ecosystems and static trends – or even declines – in boreal ecosystems have been detected since the early 1980s using coarse-scale remote sensing observations. However, intermediate-scale Landsat studies have shown that these changes are heterogeneous and may be related to landscape and regional variability in climate, land cover, topography and moisture availability. In Bonney's (MSc) study, a Landsat NDVI time series (1984-2016) was examined for a study area spanning the entirety of the transition from sub-Arctic boreal forest to Low Arctic tundra in central Canada (i.e., Great Slave Lake to the Arctic Ocean). Analysis indicated that 27 % of the study area exhibited a significant ($p < 0.05$) trend and virtually all (99.3 %) of those areas exhibited an increasing, or "greening", trend. Greening areas were most common in the northern tundra zone and the southern forest-tundra ecotone zone (Figure 12). NDVI trends were generally positive across the study area, but were smallest in the forest zone and largest in the northern tundra zone. Ground validation in the central portion of the study area revealed a strong relationship (R^2 = 0.81) between bulk vegetation volume (BVV) and NDVI for non-tree functional groups and indicated that alder *(Alnus crispa*) shrublands and open spruce (*Picea mariana* and *P. glauca*) woodland sites with shrubby understories were most likely to exhibit greening in that area. Random Forest (RF) modelling of the relationship between NDVI trends and a suite of environmental variables found that the magnitude and direction of trends differed across the forest to tundra transition. Areas that experienced large increases in summer temperature, shrubland and forest land cover types, and locations that are in close proximity to major drainage systems, further away from major lakes, or at lower elevations, generally experienced larger positive NDVI trends than other areas.

Percent vegetation cover (PVC) and the fraction of absorbed photosynthetically active radiation (fAPAR) are important functional variables for assessing Arctic vegetation density and vigor. In Dr. Liu's research, field measures of PVC, fAPAR and NDVI were collected from July 5 to August 8, 2015 along a moisture gradient in the Apex River Watershed (ARW) (63°45'N, 68°30'W), Baffin Island, Nunavut, Canada. Two field methods for estimating PVC (i.e., the point-frame and image classification methods) were examined and it was determined that the image classification approach provided a suitable alternative to the point-frame method, more specifically for detecting changes in Arctic PVC. Dr. Liu examined the spatial and temporal patterns of PVC and fAPAR in the context of NDVI derived from remote sensing data collected at different spatial resolutions. For this site, vegetation types exhibited contrasting spatial and temporal patterns of PVC as a result of differing moisture regimes: (1) vegetation types with saturated soils (e.g., sedge dominated) exhibited a continuous increase in PVC throughout the growing season; (2) mesic vegetation types with moderate soil moisture (e.g., mosses dominated with a mixture of sedges and shrubs) exhibited an increase in PVC from July to early

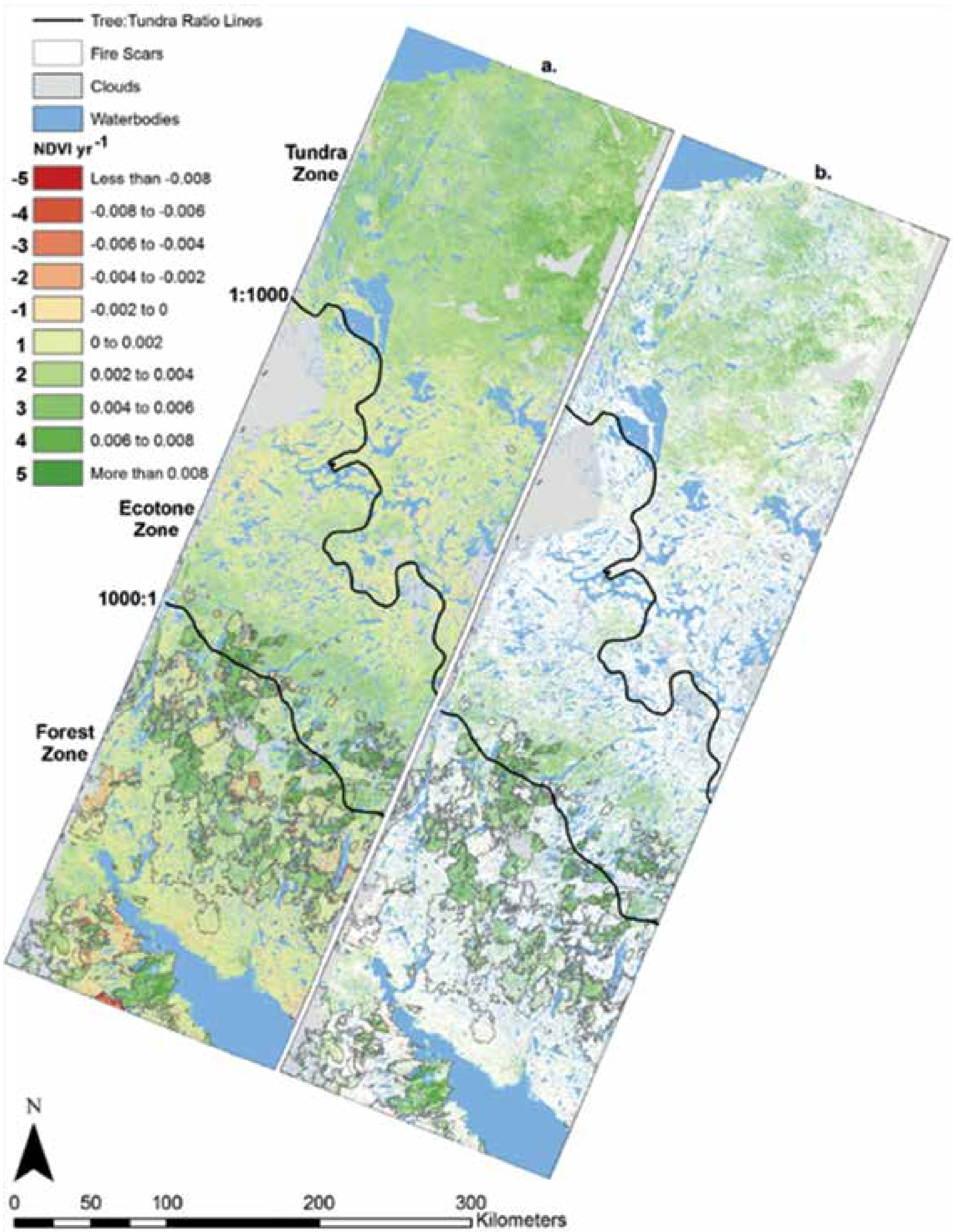

Figure 12. Landsat NDVI trends (1984-2016) for the study area as determined using ordinary least squares regression. (a) All NDVI trends. (b) Significant ($p < 0.05$) trends only. NDVI trends were binned into 10 levels for visualization purposes (-5 = most negative, 5 = most positive), as seen in the legend. Fire scars (outlined in gray) were masked and not incorporated into the analysis. Waterbodies and areas with excess cloud cover were also removed.

August followed by a decline in mid-August; and (3) semi-desert vegetation types that tended to dry early in the growing season (e.g., dominated by prostrate dwarf shrubs, herb tundra and large areas of bare soil and rock) exhibited little variation in PVC. Field measures of PVC and fAPAR demonstrated strong relationships to field NDVI data and vegetation indices (VIs) derived from 2 m-resolution WorldView-2 data, thereby providing further evidence that VIs are suitable for modelling PVC/fAPAR of Arctic vegetation.

Dr. Rudy's research examined the geomorphic processes leading to permafrost disturbance in periglacial environments. This process-based research led to the development of methodologies using terrain and remote sensing variables for detecting permafrost disturbances (including subsidence and uplift) (Figure 13) and modelling areas susceptible to permafrost disturbance. Differential interferometric

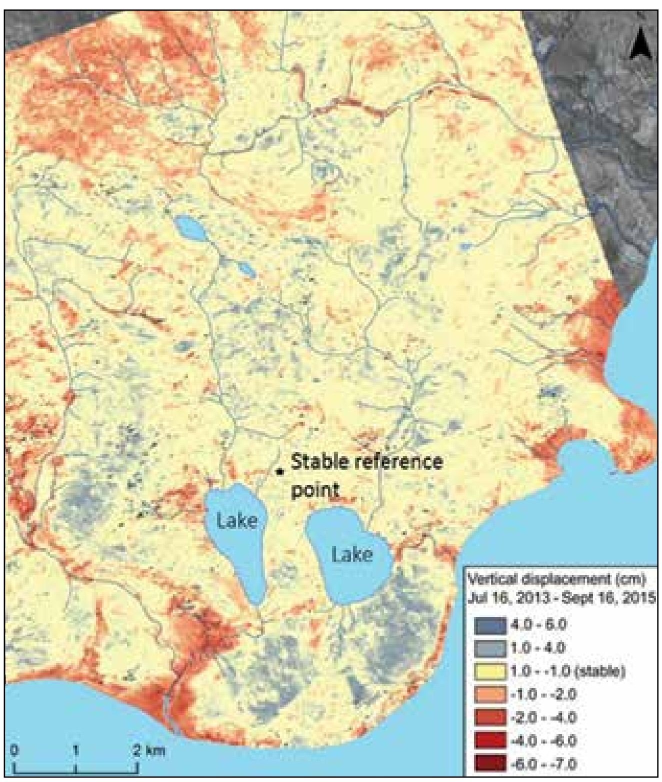

Figure 13. Inter-seasonal relief displacement derived from DInSAR (2013-2015).

SAR proved useful for identifying areas of subsidence and uplift, thereby identifying (and characterizing) areas susceptible to surface degradation as a result of permafrost thaw. Her susceptibility modelling in combination with the identification of areas of subsidence using DInSAR will provide a methodology for monitoring (and validating) permafrost environments in areas of local interest, whether these are communities or areas of other forms of infrastructure.

Niaqunquk (Apex) River

The basin wide, end-of-winter SWE was determined to be 22.7 cm ± 2.7 cm (95% confidence interval). Over the four-year record, the 95% confidence intervals

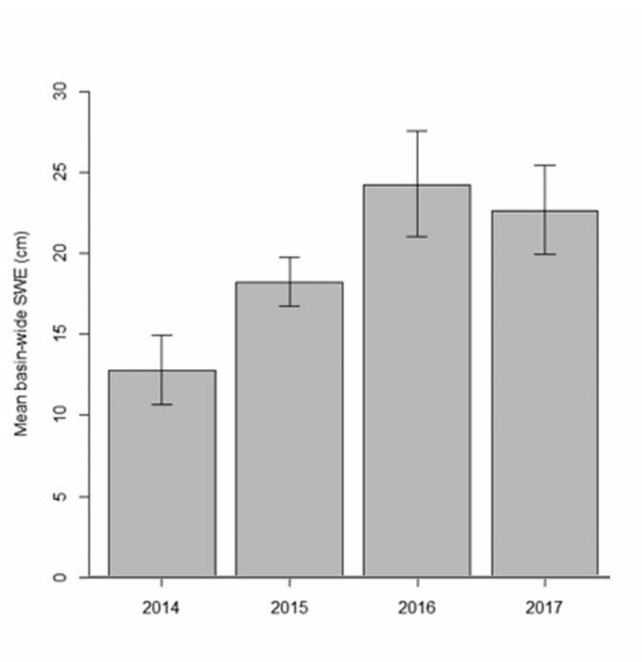

Figure 14. Mean, basin-wide end-of-winter SWE with bootstrapped, 95% confidence intervals for the Apex River watershed, 2014-207. Sample sizes were n=121, 391, 193 and 246 for 2014, 2015, 2016 and 2017, respectively. The 95% confidence intervals were, on average, 12% of the annual basin wide means. Overall, this sampling uncertainty was sufficiently to detect statistical differences between most years, but also indicative of the large sampling effort required to achieve a reliable estimate of the annual, basin-wide SWE.

for basin-wide SWE estimates were calculated with bootstrap resampling and determined to range from ±8-16% of the annual means, as shown in Figure 14. Combined with the available sample sizes in each year (see Figure 14 caption) these confidence intervals demonstrate the importance of statistically robust sampling to establish reliable estimates of basin-wide SWE for water balance modelling purposes. Wind re-distribution of snow and its interactions with the rugged topography of the Apex River watershed results in very high spatial variability of SWE and hence the need for intensive spatial sampling to achieve statistical representativeness.

Daily ET estimates for the 2017 growing season ranged from 0 mm to 2.2 mm day^{-1} (Figure 15). The total evapotranspiration flux over this period was 75 mm, which represents approximately 30% of the end-of-winter, basin wide SWE determined through snow surveying. Subsequent efforts will focus on measurement of snowpack sublimation rates

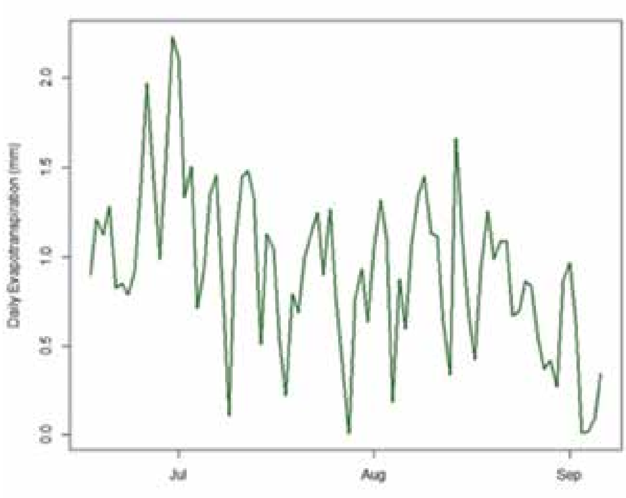

Figure 15. Daily evapotranspiration flux from EC measurements. Total growing season evapotranspiration in 2017 was 75 mm, representing approximately 30% of the total end-of-winter snow accumulation (Figure 2). In subsequent years we will deploy the EC instrumentation in May to measure the total snowpack sublimation flux over the spring melt period.

throughout the melt season, and integration of eddy covariance (EC) data into the Apex River watershed water balance by combining this new data source with snow survey results, rainfall records and streamflow discharge collected at the mouth of the river by Water Survey of Canada.

Our study results indicated that at the hillslope scale, frost table depth evolved from being shallow and spatially uniform in the early summer period, to being deeper and spatially variable later in the summer (Figure 16). Variable thaw depths had a strong association with active layer saturation patterns and our results suggested that later in the active layer thawing period the "fill-and-spill" mechanism becomes a dominant driver of hillslope hydrological connectivity in response to locally preferential active layer thaw (Figure 17). Results from our watershed scale study are pending analysis. Work to be completed during the spring and summer of 2018.

ASU Training program

Students were trained over a three-week period beginning on August 8th. Samples were taken from numerous local sites and included water, soils, sediments, and a variety of biological organisms including plants, fish and fungi. Again this year backgrounds and education levels were diverse; three of the students had a number of years of work history and two of these had primarily worked in the Arctic. Education levels ranged from high school graduates, to a student part way through her bachelor of science, to one engineering graduate. It was noted this year that the trainees were particularly engaged and were all keen to take in everything we had to offer as far as lectures went. There were frequent discussions about environmental issues and problems; at times the supposed lecture sessions bore more of a resemblance to graduate seminars.

Due to an ongoing project at the Nunavut Research Institute (NRI) involving trichinella in walrus, the laboratory used previously for the course was not always available. Much of the rudimentary

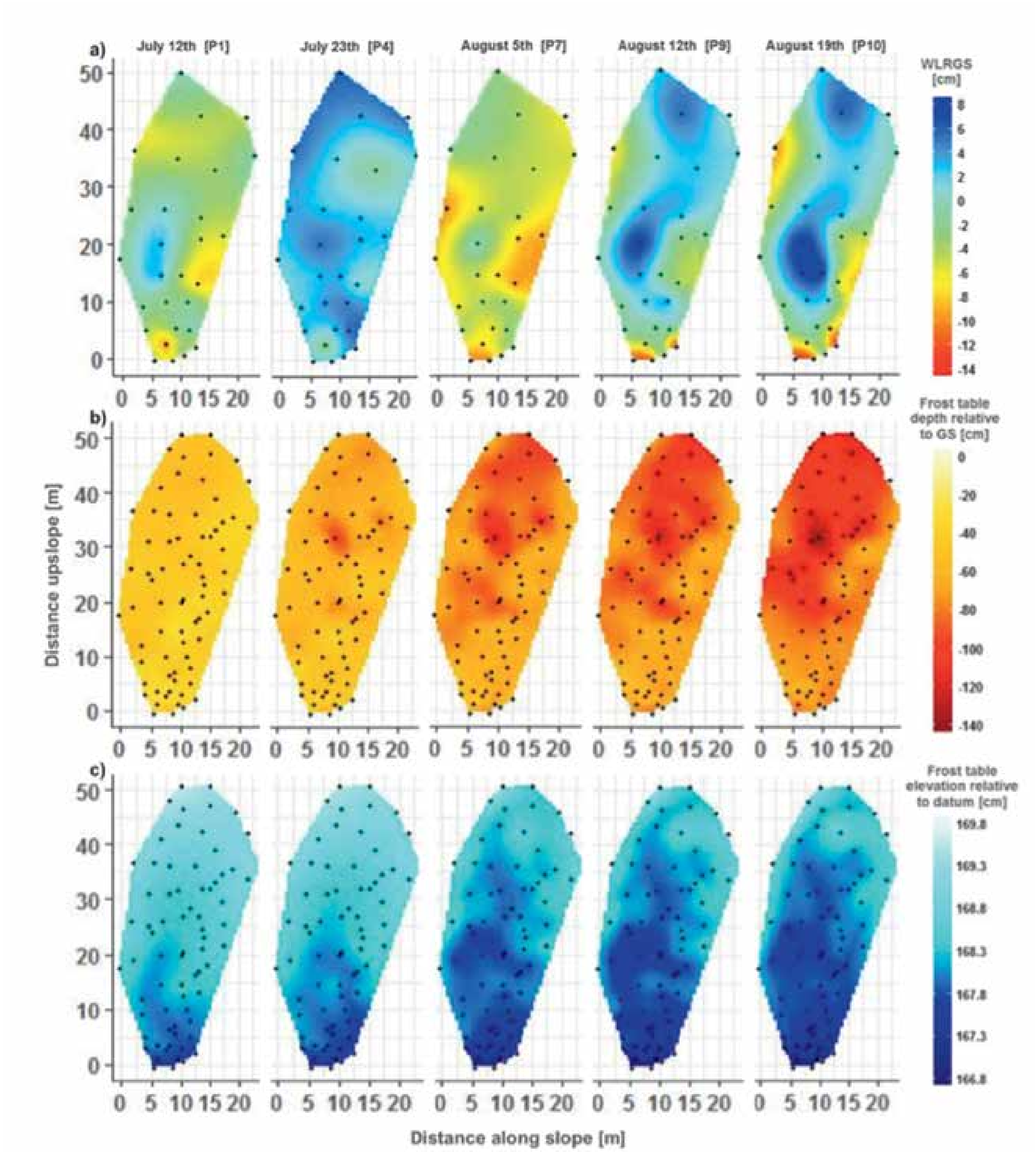

Figure 16. Nearest neighbour's interpolation showing the evolution of hillslope: a) piezometer water level relative to ground surface (WLRGS); b) frost table depth relative to ground surface (GS); and (c) frost table topography relative to local datum for a selection of 5 of the 10 sequential monitoring periods (i.e., P1, P4, P7, P9, P10). Black dots show measurements locations.

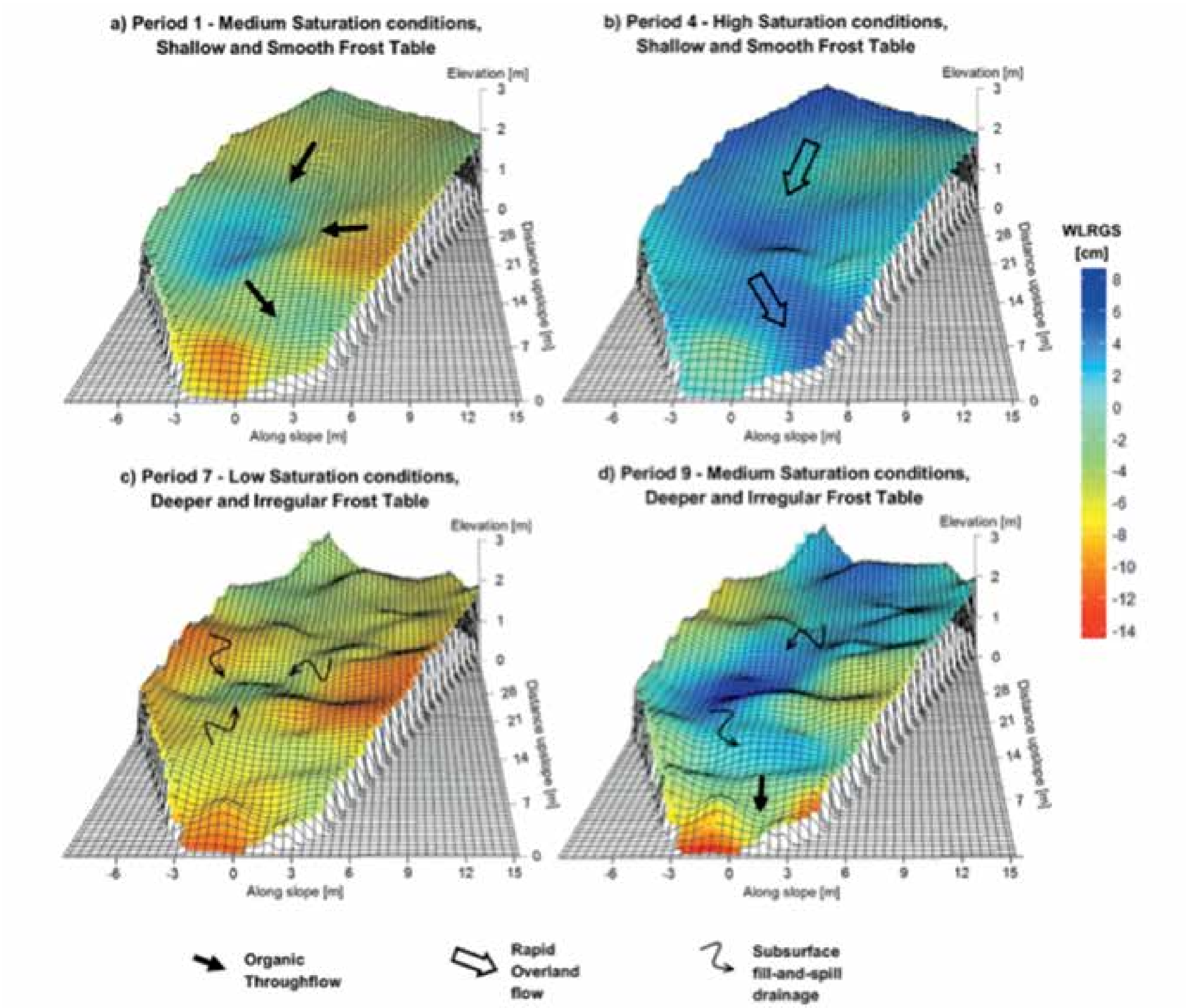

Figure 17. Conceptual representation of the evolution of hillslope drainage dynamics through the active layer thawing period. Interpolated frost table topography (see Figure 16c) are shown here using 3D grids and water level relative to ground surface (WLGRS) (see Figure 16a) using superimposed color scale. a) Shallow and smooth frost table led to hillslope drainage through surficial organic layer. b) Rapid overland flow result from high WLRGS that surpassed the surface microtopography. C) Lowering of active layer saturation led to the filling of frost table depressions. d) Rising of WLGRS reactivated downslope drainage due to spilling of frost table depressions.

laboratory work was conducted in one of the teaching laboratories of Arctic College at NRI. As well the one of the analytical instruments the x-ray fluorescence spectrometer (XRF) was moved into the teaching lab along with the shaker, and other equipment used for soil extractions.

DISCUSSION

In 2017, we undertook and completed a substantial amount of data consolidation and preparation of research syntheses for work related to CBAWO. We

Lecture/Seminar subject	Hours
Chemistry 1	1.5
Chemistry 2	1
Lab equipment and lab basics	1.5
Environmental chemistry	1
Environmental Problem Solving	1.5
Remediation - Resolution Island case study, PCBs and TPH	2
TPH Gas Chromatography /Flame Ionization Detection technique, dilutions, and calculations	1
Phytoremediation	1
Metals analysis by Atomic Absorption analysis	1
Hydrocarbon (PAH) contaminants and analysis	1

Figure 18. Course student Nysana sampling sediment and seaweed along the beach.

also initiated our first multi-year analysis of lake water quality from the Apex River watershed based on four years of sampling. These results have provided some of the most extensive data sets from the Arctic for understanding water change and sensitivity, particularly related to permafrost change. These results also were incorporated into several forthcoming IRIS 2 chapters relating to water, permafrost and water security authored by our research team.

Cape Bounty

Surface water DOM and biogeochemistry

We have consolidated and are now evaluating the long term hydroclimatic and landscape controls over runoff and changing water quality. This work is summarized in a series of published papers (Lamoureux and Lafrenière, 2017; Roberts et al., 2017; Bolduc and Lamoureux, in press) and several additional papers are in the review stage. This research demonstrates the changing hydroclimatic controls over runoff generation in the High Arctic and the key sensitivity of the system to sporadic major summer rainfall. In 11 years of hydrological monitoring, only one

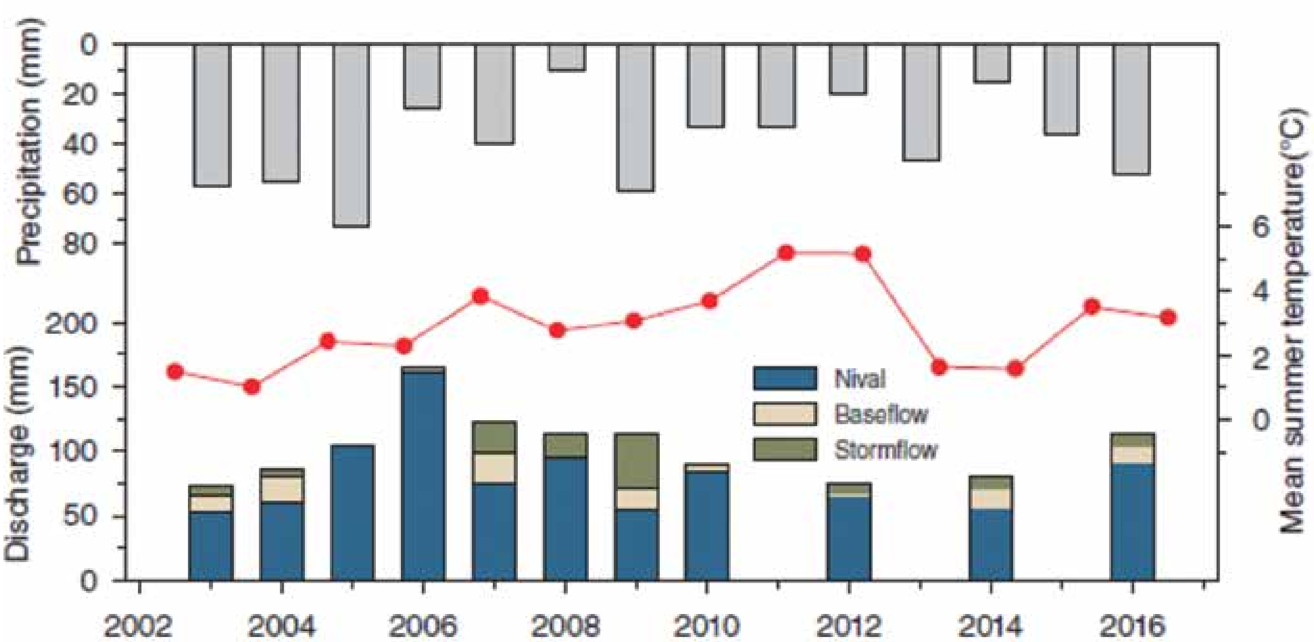

Figure 19. Long term hydrological and climate data from CBAWO. Note the variation in water source, ranging from dominantly nival (snowmelt) in 2006 to a substantial rainfall (stormflow) in 2009. From Lamoureux and Lafrenière, 2017. © 2017, John Wiley and Sons. © 2017 Wiley Periodicals, Inc.

year has experienced a significant rainfall response (Figure 19), but the consequence of this rainfall was to dominate the runoff and hydrological fluxes from the rivers (Figure 20) (Lewis et al., 2012; Lamoureux and Lafrenière, 2017).

Additional aspects of the surface water environment have been demonstrated by work at CBAWO. For example, Bolduc and Lamoureux (in press) showed a strong correlation between river temperatures and air temperatures, but noted that this relationship changed by season. Water temperatures showed varying sensitivity during the mid-summer period, and river temperatures exceeded levels considered safe for Arctic char on several occasions in warm years (Figure 21). These results, the first of their kind in the High Arctic, provide a key new element of climate change sensitivity for aquatic species and suggest the need for new work focused on thermal stress in surface waters.

The previously uncharacterized Arctic pond DOM is chemically distinct from the Arctic river DOM, with significant features of low molecular weight (reflected by E2/E3), low aromaticity (reflected by SUVA), high autochthonous contributions, low terrestrial contributions from plant and soil, and high contributions from ancient permafrost-derived organic matter. The distinct characteristics of pond DOM compared to river DOM highlights that Arctic ponds have a unique biogeochemistry that cannot be extrapolated from other types of DOM in Arctic or other aquatic systems. For example, the high autochthonous and permafrost contributions in Arctic ponds, suggest that the aged DOM is actively processed in this environment (von Wachenfeldt et al., 2008). In addition to the large difference in DOM characteristics between river and pond samples, we observed varying responses to ALDs. The difference between the undisturbed and disturbed samples indicates that ALDs alter both the pond and tributary river DOM by 1) decreasing carbohydrates and increasing CRAM in ^{1}H NMR spectra and 2) decreasing terrestrial-humic-like components and increasing oxidized-quinone-like components in the fluorescence spectra. The historic

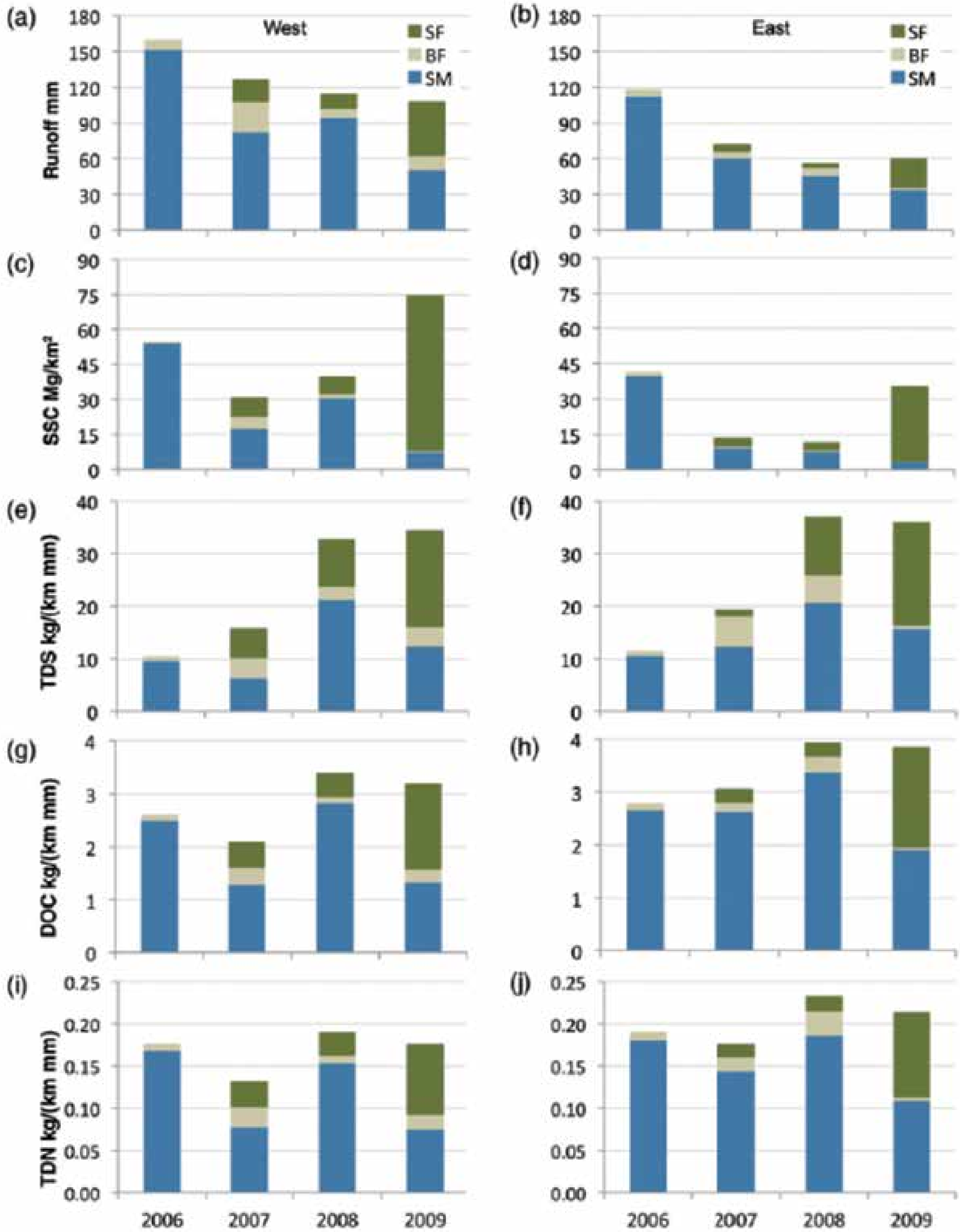

Figure 20. Suspended sediment, dissolved solids, dissolved organic carbon (DOC) and dissolved nitrogen (TDN) from the West (left) and East (right) rivers. From Lamoureux and Lafrenière, 2017. © 2017, John Wiley and Sons. © 2017 Wiley Periodicals, Inc.

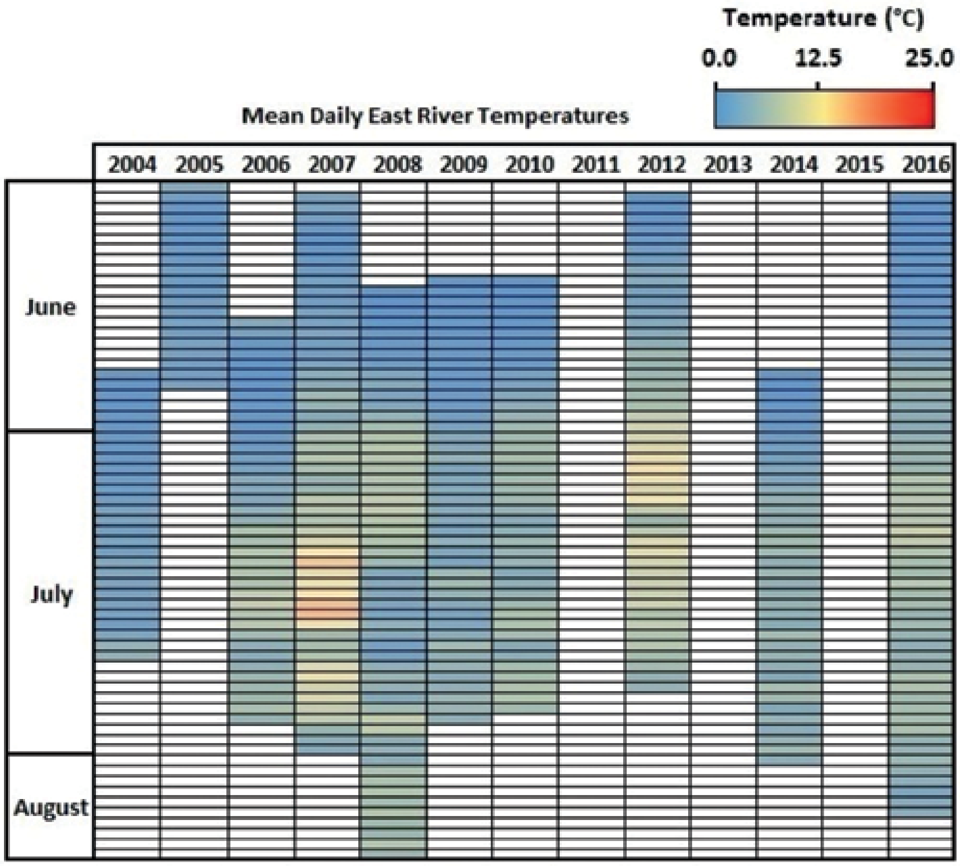

Figure 21. Daily mean temperature in the East River 2004-2016 at CBAWO. Adapted from Bolduc and Lamoureux, 2018. © Bolduc and Lamoureux 2017.

ALDs likely introduced more nutrients, which fueled microbial activity in water and caused advanced DOM degradation and oxidation. The stimulation of microbial degradation of soil and river organic matter following ALD disturbance has been previously noted and may be an important positive feedback on climate warming in the Arctic (Pautler et al., 2010; Bouchard et al., 2015). The DOM chemistry in the disturbed ponds showed the highest degree of alteration, which suggests that they may have contributed more to the positive feedback on climate warming. Following the ponds, tributary river DOM have shown similar alteration but to less degree, and the main channel receiving disturbed tributary DOM showed minor alteration compared to other main channel sites. These results suggest that with increasing physical distance from headwater to main channel, and from disturbance to channel, the impacts of terrestrial permafrost disturbance on DOM characteristics and the associated positive feedback on warming decrease. Therefore, the small Arctic ponds directly fed by permafrost DOM may be hot spots of carbon cycling and have strong positive feedback on warming via the permafrost disturbance.

As seen in previous studies, our results of the long term DIN records showed that despite relatively low DIN concentrations in snowmelt, nival runoff dominates the overall seasonal DIN flux when nival runoff is high (McNamara et al. 2008; Lafrenière & Lamoureux 2008; Lewis et al. 2012) as this period is the time of highest discharge and hydrological connectivity. The 7.8 times greater DIN flux in 2008 relative to 2007, indicates that localized disturbances can have significant impacts on DIN fluxes. The elevated fluxes of DIN in warm years and especially following rainfall, suggests that the increased active layer depth, and thaw of the transient layer, delivers DIN from this solute rich horizon in the active layer. Findings from this study suggest that when compared to physical landscape disturbances, thermal perturbations result in higher export of DIN from High Arctic environments, and this study demonstrates the impacts that different types of permafrost degradation have on the seasonality and recovery of DIN export.

Lake biogeochemistry and contaminants

Lake research at Cape Bounty has continued since 2003, with strong integration of physical, chemical and contaminant research teams. This integration has resulted in several novel collaborations across the group and important new insights into the lake environments.

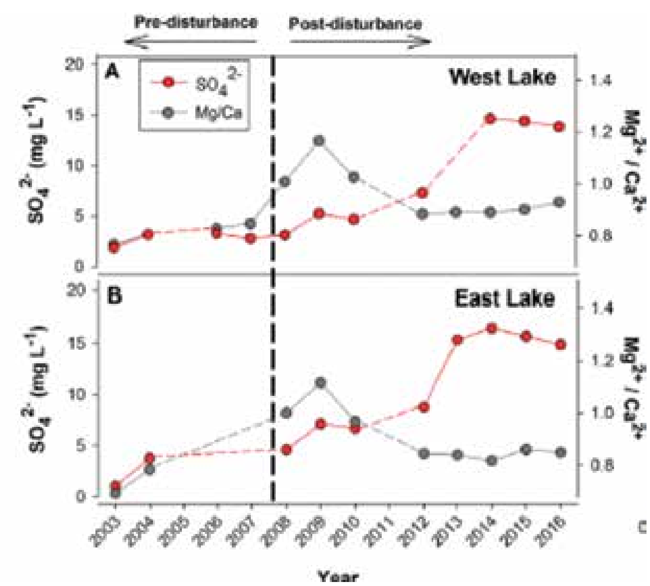

Figure 22. Long term chemical change in the lakes at CBAWO, indicating a sharp rise in SO_4, particularly after the warm year in 2012. Adapted from Roberts et al., 2017. © Roberts, Lamoureux, Kyser, Muir, Lafrenière, Iqaluk, Pieńkowski, Normandeau 2017.

Concentrations of CO_2 in the surface waters of East and West lakes were always above atmospheric equilibrium, resulting in both these systems being constant sources of CO_2 to the atmosphere. This means that, overall, net rates of decomposition of organic carbon in these lakes is greater than net rates of primary productivity. Concentrations of CO_2 are higher in the bottom waters of West Lake, clearly showing that there is biological decomposition of organic matter in the sediments of this cold lake. Methane concentrations tend to be much higher in East Lake than in West Lake, suggesting that anaerobic decomposition is greater in East Lake.

Long term water column chemistry in both lakes shows abrupt changes, indicating a large transfer of dissolved solids that has accumulated. This chemical transfer is most notable in the 2012/13 period, when many elements in the lakes increase sharply. For instance, SO_4^{2-} increases a total of 500% in the West Lake and 380% in the East Lake, with most of the change occurring after the record warm years of 2011 and 2012 (Figure 22) (Roberts et al., 2017). These changes notably occur after the permafrost surface disturbance event in 2007, and indicate the importance of deep thaw and related mobilization of dissolved material from the transition layer and upper permafrost. Effectively, the lake chemistry changed abruptly and at a scale previously unknown in the Arctic (Figure 22) (Roberts et al., 2017).

Investigations with otoliths (ear bones) from Arctic char available from contaminant research, revealed a correlative change in otolith microchemical composition at the same time as the lake water changes (Figure 23). While the precise physiological implications of these changes remain poorly understood (Roberts et al., 2017), the evidence that the char in the lakes are responding to permafrost-induced water chemistry changes requires further investigation (currently underway and planned by team members).

Further work in the lakes has indicated that our preliminary conclusion is that permafrost disturbance in its catchment and subaqueous slumping of sediments in West Lake itself have resulted in higher

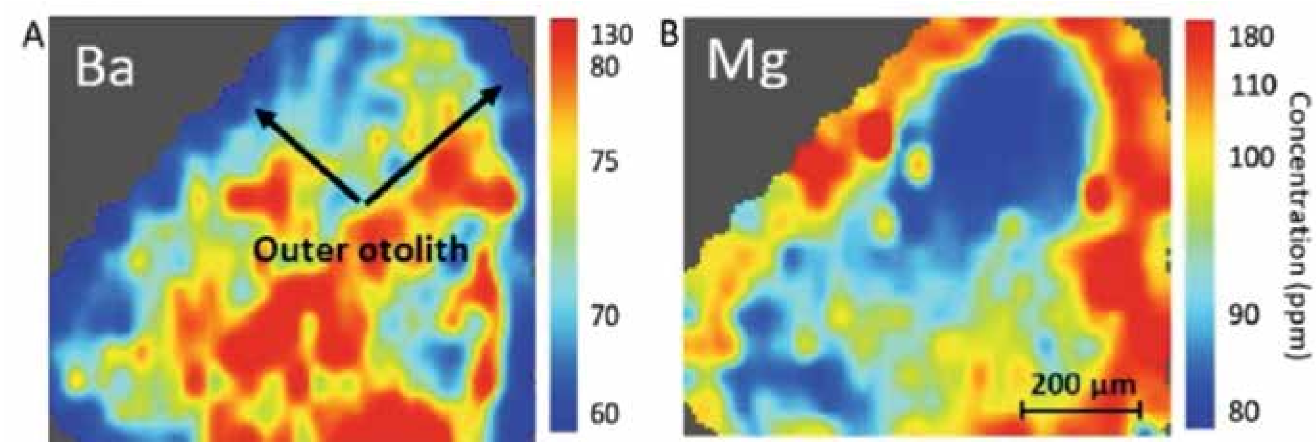

Figure 23. Example of otolith (ear bone) micro-chemistry from Arctic char in the East Lake, CBAWO. The abrupt change in elemental chemistry in the otoliths is observed in fish from both lakes and indicates a physiological response of the fish to related water chemistry changes. Adapted from Roberts et al., 2017. © Roberts, Lamoureux, Kyser, Muir, Lafrenière, Iqaluk, Pieńkowski, Normandeau 2017.

concentrations in char of THg and other elements known to have bioaccumulation potential. Similarly, physio-chemical properties are key to explaining differences in observed trends among the organic contaminants. PCBs/DDTs have much greater hydrophobicity and stronger partitioning to soil/sediment organic carbon than PFASs or HCHs.Greater inputs via mobilization of POPs associated with dissolved and particulate organic carbon from the catchment and lake sediments are likely occurring.

Much higher turbidity in West Lake from 2009 to 2017 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.

Terrestrial vegetation and soil systems

Future global climate change predictions depend on quantifying feedbacks throughout the circumpolar Arctic. Our research will continue to produce data to help us understand how these ecosystems work. We continue to participate in synthesis studies to ensure the broadest impact of our findings and dataset (e.g. Lafleur et al. 2012). We are also working on collaborations where we can contribute to national and international modeling groups which will ensure our results help improve climate change adaptation and mitigation efforts as GCM models better incorporate these important high-latitude feedbacks. This knowledge is critical for people in Canada's North working to adapt to change in their environment as well as for communities around the globe that must have confidence in these predictions to support reductions in greenhouse gas emissions and take the steps needed to prepare for future climate change.

One of the predictions is that snowfall rates may increase in the Arctic in response to climate change. This could lead to an increase in soil moisture levels. While the production of nitrate in soils is often low to non-existent in Arctic soils, our results show significant concentrations of soil nitrate, and that they are higher in areas with higher soil moisture. This suggests that soil nitrate levels could increase in the future with increases in soil moisture. This could lead to higher concentrations of nitrate in surface waters and a degradation in water quality.

Our results also provide insights into the contribution of the High Arctic to further changes in climate. While warming temperatures could lead to an increase in soil organic matter turnover, and release of carbon dioxide to the atmosphere, organic matter decay can also release nutrients into the soil, stimulating plant growth (and carbon removal from the atmosphere). This would only happen if plant growth is nitrogen limited. Our results indicate that plant growth in wet-sedge communities in the High Arctic is nitrogen limited, and that plant growth is higher in areas with higher concentrations of soil nitrogen. Furthermore, concentrations of soil nitrogen were higher in areas with higher soil moisture levels. This suggests that future changes in soil moisture driven by increased snowfall could lead to increased plant growth and removal of carbon from the atmosphere, a negative feedback on the climate system.

Given summer mean temperatures are near freezing in the Canadian High Arctic, a few degrees shift in summer air temperatures 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, phytomass, 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, first within the context of vegetation change, and secondly permafrost. 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 productivity and stability, but also in the context of biospheric 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 multiples scale is essential to understanding the response of these ecosystems to warming. Deriving biogeophysical 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 North.

Niaqunguk (Apex) River

Currently there is a critical lack of historical snow accumulation data for Southern Baffin Island. We have successfully initiated a new end-of-winter SWE accumulation for the 52 km^2 Apex River watershed, and the protocol established in collaboration with NAC ETP will be used on an annual basis to continue this record. Similarly, our EC measurements represent the first continuous growing season record of evapotranspiration for Canada's northeastern Arctic. These data sources will provide invaluable physical hydrology information on the Apex River water balance, which will be used as a model system to understand impacts of climate change on renewable freshwater resource supply in the Iqaluit region.

With regards to our hillslope research, results show that uneven thawing can lead to the development of an irregular frost table that exerts a strong influence on the storage and routing of surface and subsurface flows at the hillslope scale. This knowledge of the spatiotemporal temporal evolution of hillslope drainage dynamics is critical for modelling and projecting the response of arctic river systems to climate change. Continued work to evaluate the larger catchment controls over water sources and sensitivities continue.

As part of the ASU water training program, the trainees were able to use and achieve competence working with a variety of instruments and equipment such as balances, pipettes, temperature sensors, syringes as well as more sophisticated analytical instruments such as the XRF and the gas chromatograph (GC). This year the course participants were also able to take advantage

Figure 24. Jason prepping sample for the mercury analyzer.

Figure 25. Sampling soils, sediment and biological tissues by the Iqaluit airport.

of a new DMA-80 Mercury analyzer that was recently acquired by Nunavut Research Institute. Mercury was a very popular method in the course because soil, water, and tissue can be analyzed easily with minimal preparation.

By the completion of the course students gained proficiency in carrying out three analytical methods, Mercury in Liquids, Soil, Plants and Tissues, Total

Figure 26. Mary, Jason and Garrett grinding up dried samples in preparation for analyses.

Petroleum Hydrocarbons (TPH) in Soil, and Metals in Soil by X-Ray Fluorescence Spectrometry (XRF). The prep work for Metals by AA was also completed, but due to technical difficulties, the samples could not be analyzed. Throughout the course results from the various analyses were frequently compared with the relevant government regulations (e.g. CCME) to give the students applicable context.

The students enjoyed field sampling a great deal and there were often surprises. Areas hypothesized to have significant hydrocarbon contamination for example came up clean. Subsequently, some presumably safe edible plants showed significant levels of metals contamination. Samples of locally caught fish were also analyzed and shown to be well within regulation limits for mercury in commercial seafood. The most interesting example of unexpected results was undoubtedly the mercury concentrations in large "puffball" mushrooms.These were sampled from two areas; one near the airport and other on the road to Apex. Analysis of the large puffballs showed levels of mercury that were double the regulatory limits for mercury in commercial seafood. Interestingly, the mercury levels in the soil surrounding the mushrooms were extremely low. While some mercury concentrations were also found in nearby plants and other smaller mushrooms, the large "puffballs" were the highest by far. This is perhaps not so unexpected as some types of fungi are known to accumulate metals. Nevertheless, students remarked that they would likely think twice about eating those theoretically edible mushrooms from now on.

Prompted by the results from mercury measurements in mushrooms, plans are in the works to fund a small research project that would function as a component of the 2018 summer training program. The project would further investigate mercury levels in edible biological samples from tundra in around Iqaluit. It is anticipated this sort of project would generate even more enthusiasm and add context for trainees taking the course. Local sampling has always been popular with trainees and the unsolicited reviews we received for the 2017 program are encouraging.

CONCLUSION

Research activities for this project during 2017-18 and throughout the 2015-18 period of the full project 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. Work in 2017-18 in particular has resulted in important, multi-year syntheses of land and water research and contributed to the forthcoming ArcticNet IRIS 2 report.

The value of this work has translated into the establishment of our Niaqunguk (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. This work, started in 2013, has gained momentum and partners. 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.

Of particular note, our results support our original hypothesis that climate-related changes, may alter fluxes of toxic and bioaccumulative substances to Arctic freshwater systems. The fact that this is observed not only for mercury but also for other elements (cesium, rubidium, thallium) and for persistent organic pollutants is a concern. Most High Arctic communities depend on freshwater supplies from lakes that could eventually be impacted by similar disturbances. Similarly, the decline in fish condition and increase in THg and POPs concentrations are a potential concern for human and wildlife consumers. Whether these changes in contaminants or condition of the landlocked char are widespread across Nunavut is not known; 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.

Remote sensing methods have also proven crucial to the mapping, modelling and monitoring of a range of biophysical variables on land that are relevant for land and water management. Our field work is unique and instrumental in calibrating methods and models for generating spatially-explicit biophysical variables, methods that appear to be transferable to other locations within the Arctic.

In conclusion, our state of the art research to understand the implications of climate and permafrost change, and will also offer further syntheses of long term datasets in the rivers, sediment transport, contaminants and remote sensing indicators of change. Our research group will continue to expand efforts to engage and directly involve the Resolute community, through social media and town visits.

ACKNOWLEDGEMENTS

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REFERENCES

Bolduc, C., Lamoureux, S.F. and Franssen, J., 2018. Thermal and isotopic evidence for surface and subsurface water contributions to baseflow in a High Arctic river. Hydrological Processes, 32:602–616, doi:10.1002/hyp.11427.

Bolduc, C. and Lamoureux, S.F., 2018. Multi-year variations in High Arctic river temperatures in response to climate variability. Arctic Science, https://doi.org/10.1139/AS-2017-0053.

Bonan G.B. 1995. Land–atmosphere CO_2 exchange simulated by a land surface process model coupled to an atmospheric general circulation model. Journal of Geophysical Research, 100D: 2817–2831.

Bouchard, F, Laurion, I, Prekienis, V, Fortier, D, Xu, X, Whiticar, MJ. 2015. Modern to millennium-old greenhouse gases emitted from ponds and lakes of the Eastern Canadian Arctic (Bylot Island, Nunavut). Biogeosciences 12:7279-7298.

Lafleur, P.M., Humphreys, E.R., Myklebust, M.C., St. Louis, V.L., Papakyriakou, T., Poissant, L., Barker, J.D., Pilote, M. and Swystun, K.A. (2012). Variation in peak growing season net ecosystem production across the Canadian Arctic. Environmental Science and Technology, doi.org/10.1021/es300500m.

Lafrenière, M.J. and Lamoureux, S.F. (2008) Seasonal dynamics of dissolved nitrogen exports from two High Arctic watersheds, Melville Island, Canada. Hydrology Research 39(4), 323-335.

Lafrenière, M.J. and Lamoureux, S.F. (2013) Thermal perturbation and rainfall runoff have greater impact on seasonal solute loads than physical disturbance of the active layer. Permafrost and Periglacial Processes 24, 241-251.

Lamoureux, S.F., Lafrenière, M.J. and Favaro, E. (2014) Erosion dynamics following localized permafrost slope disturbances Geophysical Research Letters, 2014GL060677R.

Lamoureux, S.F. and Lafrenière, M.J. (2017) More than just snowmelt: integrated watershed science for changing climate and permafrost at the Cape Bounty Arctic Watershed Observatory. Wiley Interdisciplinary Reviews: Water 5(1), e1255.

Lewis, T., Lafrenière, M.J. and Lamoureux, S.F. (2012) Hydrochemical and sedimentary responses of paired High Arctic watersheds to unusual climate and permafrost disturbance, Cape Bounty, Melville Island, Canada. Hydrological Processes 26(13), 2003-2018.

Louiseize, N.L., Lafrenière, M.J. and Hastings, M.G. (2014) Stable isotopic evidence of enhanced export of microbially derived NO_-^{3-} following active layer slope disturbance in the Canadian High Arctic. Biogeochemistry 121(3), 565-580.

McNamara, J.P., Kane, D.L., Hobbie, J.E. and Kling, G.W. (2008) Hydrologic and biogeochemical controls on the spatial and temporal patterns of nitrogen and phosphorus in the Kuparuk River, arctic Alaska. Hydrological Processes 78, 173-193.

Pautler, BG, Simpson, AJ, McNally, DJ, Lamoureux, SF, Simpson, MJ. 2010. Arctic Permafrost Active Layer Detachments Stimulate Microbial Activity and Degradation of Soil Organic Matter. Environmental Science and Technology 44:4076-4082.

Roberts, K.E., Lamoureux, S.F., Kyser, T.K., Muir, D.C.G., Lafrenière, M.J., Iqaluk, D., Pieńkowski, A.J. and Normandeau, A. (2017) Climate and permafrost effects on the chemistry and ecosystems of High Arctic Lakes. Scientific Reports 7(1), 13292.

von Wachenfeldt, E, Sobek, S, Bastviken, D, Tranvik, LJ. 2008. Linking allochthonous dissolved organic matter and boreal lake sediment carbon sequestration: The role of light mediated flocculation. Limnology and Oceanography 53:2416-2426.

Walker, D., et al., 2005. The circumpolar arctic vegetation map. J. of Veg. Sci., 16:267-282.

Wang, J.-J., Lafrenière, M.J., Lamoureux, S.F., Simpson, A.J., Gélinas, Y. and Simpson, M.J. (2018) Differences in riverine and pond water dissolved organic matter composition and sources in Canadian High Arctic watersheds affected by active layer detachments. Environmental Science & Technology, 10.1021/acs.est.1027b05506.

PUBLICATIONS

Atkinson D, Gregory F, Scott NA, Treitz P. (submitted) High spatial resolution remote sensing models for landscape-scale CO_2 exchange in the Canadian High Arctic. Biogeosciences (in review).

Lamoureux SF, Lafrenière MJ (2018) More than just snowmelt: integrated watershed science for changing climate and permafrost at the Cape Bounty Arctic Watershed Observatory. Wiley Interdisciplinary Reviews: Water 5(1).

Lamhonwah D, Lafrenière MJ, Lamoureux SF, Wolfe B (2017) Evaluating the hydrological and hydrochemical responses of a High Arctic catchment during an exceptionally warm summer. Hydrological Processes 31, 2296-2313.

Lafrenière MJ, Louiseize NL, Lamoureux SF (2017) Active layer slope disturbances affect seasonality and composition of dissolved nitrogen export from High Arctic headwater catchments. Arctic Science 3(2), 429-450.

Inglese C, Christiansen CT, Lamhonwah D, Moniz K, Montross S, Lamoureux SF, Lafrenière MJ, Grogan P, Walker VK (2017) Examination of soil microbial communities after permafrost thaw subsequent to an active layer detachment in the High Arctic. Arctic, Antarctic and Alpine Research 49(3), 455-472.

Fouché J, Lafrenière MJ, Rutherford K, Lamoureux SF (2017) Seasonal hydrology and permafrost disturbance impacts on dissolved organic matter composition in High Arctic headwater catchments. Arctic Science 3(2), 378-405.

Gillman MA, Lamoureux SF, Lafrenière MJ (2017) Calibration of a modified temperature-light intensity logger for quantifying water electrical conductivity. Water Resources Research 53(9), 8120-8126.

Chiasson-Poirier G, Franssen J, Legendre, P. (submitted) Linking physical controls on hillslope drainage with spatial extent of hydrological connectivity during the active layer thawing period. Water Resources Research.

Rudy ACA, Lamoureux SF, Treitz, PM, Short N, Brisco B (2018) Seasonal and multi-year surface displacements measured by DInSAR in a High Arctic permafrost environment. International Journal of Applied Earth Observation and Geoinformation 64, 51-61.

Edwards R, Treitz PM (2017) Vegetation greening trends at two sites in the Canadian Arctic: 1984-2015. Arctic, Antarctic and Alpine Research 49(4), 601-619.

Holloway JE, Rudy ACA, Lamoureux SF, Treitz PM (2017) Determining the terrain characteristics related to the surface expression of subsurface water pressurization in permafrost landscapes using susceptibility modelling. The Cryosphere 11, 1403-1415.

Liu N, Budkewitsch P, Treitz PM (2017) Examining spectral reflectance features related to Arctic percent vegetation cover: Implications for hyperspectral remote sensing of Arctic tundra. Remote Sensing of Environment, 192, 58-72.

Rudy ACA, Lamoureux SF, Treitz PM, Van Ewijk K, Bonnaventure PP, Budkewitsch P (2017) Terrain controls and landscape-scale modelling of active-layer detachments, Sabine Peninsula, Melville Island, Nunavut. Permafrost and Periglacial Processes, 28, 79-91.

Hung JKY, Atkinson DM, Scott NA. (submitted) Available nitrogen and environmental controls on carbon exchange in a High Arctic wetland. Biogeosciences (in review).

Wang J-J, Lafrenière MJ, Lamoureux SF, Simpson AJ, Gélinas Y, Simpson MJ. (2018) Differences in riverine and pond water dissolved organic matter composition and sources in Canadian High Arctic watersheds affected by active layer detachments. Environmental Science & Technology (in press), 10.1021/acs.est.1027b05506.

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PROVIDING CLIMATE SCENARIOS FOR THE CANADIAN ARCTIC WITH IMPROVED POST-PROCESSING METHODS

Project Team

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ABSTRACT

Planning and adapting to a warming Arctic requires the best information on potential 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. 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. Climate simulations must therefore be post-processed to obtain statistical properties similar to those of observed time series. The objective of this project is to provide 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 are aimed 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.

KEY MESSAGES

Key messages have been organized in terms of the main topics of the study: 1. Climate indicators in historical and future climate (A. Mailhot); 2. Post-processing methods (P. Grenier); 3. Defining reference climates by combining observational datasets and reanalysis (A. Mailhot); 4. Modeling of wave and fast ice dynamics in Baffin Bay and Hudson Bay (D. Dumont). Please note that the redaction of the various sections related to each of the preceding topics were under the responsibility of the scientific coordinator of these topics indicated in parenthesis.

Climate indicators in historical and future climate

- A total of 51 climate indicators were considered (21 temperature, 12 total precipitation, 9 liquid and solid precipitation, and 5 snow depth indicators, and 5 wind indicators).
- Projected changes for all climate indicators were estimated for two emission scenarios (RCP 4.5, a low emission scenario and RCP 8.5, a high emission scenario) and two future periods (mid-century period – 2040-2064 - and end of the century period - 2076-2100). Changes are expressed as absolute differences in mean climate indicators over the future period and reference period (1980-2004).
- The ensemble of regional climate models projects important changes for the vast majority of the 47 climate indicators not related to wind.
- The two emission scenarios display similar changes for the mid-century but important differences between these two scenarios are observed at the end of century; the largest changes are projected for the end of the century for the RCP 8.5 scenario.
- Differences between the two forcing scenarios are especially important for climate indicators related to winter (e.g., annual fraction of solid precipitation, freezing degree days, heating degree days, snow cover duration, December-January-February mean temperature) and to extremes (e.g., 99th percentile of daily precipitation, extremely wet days, precipitation on extremely wet days, frequency of warm nights, extreme cold nights).
- All regional models agree on increasing mean seasonal, annual, maximum and minimum temperatures over the IRIS-4 region. The median value of the simulated mean regional change for RCP 8.5, for the end of the century period, is 6.7°C for annual mean temperature, 10.5°C for winter temperature and 5.2°C for summer temperature.
- The number of freezing days will decrease by -51 days by the end of the century (RCP 8.5) in average over the IRIS-4 region while the average regional value in historical climate (1980-2004) is 164 days (relative decrease of 31%).
- Annual mean total precipitation and extreme precipitation will both increase with extremes increasing more than average annual mean precipitation. For the end of the century, the median value of the projected mean regional change in annual mean total precipitation for RCP 8.5 is 0.7 mm/day, while the average regional value in historical climate is 2 mm/day. The projected regional mean change for R99pTOT index (precipitation due to extremely wet days) is 78 mm with a value of 43 mm for the reference period.
- Projected changes in annual mean solid precipitation over the IRIS-4 region are small and simulations disagree on the sign of the climatic change.
- Important changes are projected for the snow cover duration which is expected to drastically decrease. The median of the projected regional mean change at the end of the century for RCP 8.5 is -60 days (the regional annual mean duration of snow cover for the reference period is 216 days).

Snow cover will in average start later during the year and finish at an earlier date.

- For the two emission scenarios and the two future periods (2040-2064 and 2076-2100), changes in wind indicators over IRIS-4 are relatively small but more likely positive.
- For IRIS-4, the four wind indicators selected are: annual average of daily average wind (Wavgavg); annual average of daily maximum wind (Wavgmax); annual maximum of daily maximum wind (Wmaxmax), and the number of days for which maximum wind exceeds force 6-39 km/hr – on Beaufort scale (NBeaufort6).
- For wind indicators over IRIS-4, only 11 ECCC stations can be used (at least 15 years with 80% valid daily data); these data were used to assess reanalysis biases for indicators based on daily wind values, but not for indicators based on daily extreme wind. Several criteria led to the choice of CFSR as the reference product for wind indicators (other investigated reanalysis were ERA-Interim, JRA-55 and MERRA-2).
- For two emission scenarios (RCP4.5 and RCP8.5) and two future periods (2040-2064 and 2076-2100), changes in wind indicators over IRIS-4 are relatively small but more likely positive.
- Mean near-surface wind speeds over Baffin Bay/ Davis Strait are projected to change within a ±5% range by 2030 and within a ±10% range by 2080 for all seasons.

Post-processing methods

- Temperature and precipitation are correlated during winter at many Arctic sites, and this is often not well represented by climate models and not corrected by basic univariate quantile mapping (QM) post-processing method.
- It has been shown that simple bivariate QM can correct correlations as efficiently as much more complex methods.
- Simulated long-term trends may be altered by basic QM but some adaptation of the QM approach can be made to preserve long-term trend.
- Month-specific correction functions could lead to climatological discontinuities between month-to-month adjacent days; day-specific correction functions are now used to avoid such discontinuities.
- QM can generate physical inconsistency between daily temperature extrema (i.e., daily Tmin > daily Tmax); three methods to circumvent this problem have been investigated, and it was concluded that the best option overall was to post-process Tmax and the diurnal temperature range (DTR = Tmax - Tmin), and next estimate Tmin; it was also concluded that one cannot completely avoid the physical inconsistency problem simply by tuning options and parameters of the QM technique.
- The generation of single-variable and inter-variable physical inconsistency for humidity variable has been investigated for 12 North American sites; this problem has been characterized, and recommendations have been made; although the study was not specific to the Arctic, both Iqaluit (NU) and Yellowknife (NWT) were included as test sites, and therefore recommended post-processing improvements are also relevant for the Arctic.
- Relationships between recent-past sea ice cover and long-term temperature trends in a large ensemble of simulations have been found for sea ice transition months over Hudson Bay (December, January, June, July); this could potentially lead to selection of simulations based on recent-past performance (so-called emergent constraints), but the related master’s thesis is not finished and will extend until next September.

Defining reference climates by combining observational and reanalysis datasets

- Defining a reference climate is an important issue for climate change impact and the development of adaptation strategies.
- It remains a challenge in regions that were historically poorly covered by meteorological stations such as Arctic Canada.
- Reanalyses represent an interesting option to define a reference climate in such regions however validation and post-processing of these datasets are needed because of inherent biases.
- Reference climate mean values over a 30-year period (1980-2009) for ten climate precipitations indicators were defined by combining reanalysis and observational datasets using Optimal Interpolation (OI) and Ensemble Optimal Interpolation (EnOI) methods.
- Cross-validation strategy was applied and showed that the developed reference dataset improve our ability to estimate climate precipitation indicators at sites where no recorded precipitations are available.

Modeling of wave and fast ice dynamics in Baffin Bay and Hudson

- An ensemble of six simulations (3-h time steps) has been used for building gridded climate scenarios (temperature, zonal and meridional winds) over Hudson Bay, for subsequent use in wave and sea ice impact models; these scenarios cover changes between +2 and + 10°C for area-average mean temperature, and changes between +0.1 and +0.5 m/s for area-average mean wind speed (1979-2010 compared to 2069-2100), with a strong positive correlation between temperature change and wind change.
- Simulated climate change in winds generally show discontinuities at land/sea interface, with maritime grid tiles having larger changes than adjacent land grid-point; this raised questions regarding the best way to build scenarios for wind climate change at coastal sites, but this issue could not be investigated completely in this project.
- Latest knowledge and parameterizations of wave-ice interactions have been integrated into state-of-the-art numerical models using a wisely selected set of regional climate scenarios to produce, for the very first time, a reference climate and evaluate climate change indicators relevant for coastal communities and stakeholders in Nunavik and around the Hudson Bay system.
- Coastal marine climate will very likely significantly change over the next century. The ice covered season will shorten, allowing stronger late fall and early spring winds to generate larger waves that will impact the coast.
- The adopted methodology is based on open-access and community-based models that will continue to take-up new knowledge generated by the international community such that this endeavour can be reproduced and even partially automated to update the climate change assessment.

RESEARCH OBJECTIVES

Research objectives have been organized in term of the main topics of the study: 1. Climate indicators in historical and future climate; 2. Post-processing methods; 3. Development of scenarios combining reference datasets; 4. Modeling of wave and fast ice dynamics in Baffin Bay and Hudson Bay.

1. Climate indicators in historical and future climate:
    - 1.1. Upgrade and gather the most recent regional climate simulations and new datasets combining reanalysis and observational datasets.

1.2. Estimate and compare climate indicators in observational datasets and simulations, and select the datasets defining the reference climate.

1.3. Compare and select a post-processing method to be used for climate projections.

1.4. Develop climate projections for all climate indicators for two future periods (2040-2064 and 2076-2100) and two radiative forcing scenarios (RCP 4.5 and RCP 8.5).

2. Post-processing methods:

   2.1. Implement multivariate post-processing methods and investigate their added value.

   2.2. Investigate the issue of inter-variable physical consistency involved in statistical post-processing and make recommendations for climate services.

   2.3. Apply post-processing methods to less-investigated climate variables (e.g. wind, humidity).

   2.4. Investigate the value added by performance-based selection of simulations (prior to post-processing).

3. Defining reference climates by combining observational and reanalysis datasets:

   3.1. Define reference climate for precipitation indicators by combining station records and reanalysis using the using Optimal Interpolation (OI) and Ensemble Optimal Interpolation (EnOI) methods.

   3.2. Compare the precipitation indicators from the OI (each reanalysis combined to station records) and EnOI dataset (all four reanalyses combined to station records) to corresponding indicators at station sites.

   3.3. Use cross-validation approach to estimate the performance of OI and EnOI datasets at validation sites.

4. Modeling of wave and fast ice dynamics in Baffin Bay and Hudson Bay:

   4.1. Develop relevant wave and sea ice indicators for the coastal climate.

   4.2. Implement wave-ice interactions in model WAVEWATCH III.

   4.3. Use post-processed climate scenarios to simulate sea ice and wave dynamics in Hudson Bay.

   4.4. Produce reference climate indicators for coastal wave and sea ice.

   4.5. Assess the impact of climate change on coastal wave and sea ice through coastal climate indicators.

KNOWLEDGE MOBILIZATION

- Barrette C., Brown R., Way R. (2017). Updated climate information for Nunavik and Nunatsiavut IRIS region. Oral presentation, Arctic Change 2017 conference, Québec (Canada), December 12-15, 2017.
- Diaconescu E.P., Mailhot A., Chaumont D., Brown R. (2017). Climate scenarios for Nunavik based on regional climate model simulations from CORDEX. Oral presentation, Arctic Change 2017 Conference, Québec (Canada), December 11-15, 2017.
- Diaconescu E.P., Mailhot A., Chaumont D., Brown R. (2017). Développement de scénarios climatiques pour le Canada basés sur les simulations régionales CORDEX. Oral presentation, 7e Symposium Ouranos, Plaza Centre-Ville, Montréal, (Canada), November 15-17, 2017.
- Charron I. (2017). Portrait climatique au Nunavik: changements en cours et attendus. Oral presentation, 7e Symposium Ouranos, Plaza Centre-Ville, Montréal, (Canada), November 15-17, 2017.

- Sévigny C., Dumont D., Senneville, S., St-Onge-Drouin, S., Grenier, P., Ardhuin F. (2017). Projected changes in the wave and sea ice climate along the coastal Hudson Bay. Oral presentation, Arctic Change 2017 conference, Québec (Canada), December 12-15, 2017.
- Giguère V., Grenier P. (2017). Développement de contraintes émergentes pour réduire l'incertitude des scénarios de température de la région de la Baie d'Hudson. Poster, 7e Symposium Ouranos, Plaza Centre-Ville, Montréal, Québec (Canada), November 15-17, 2017.
- Grenier P. (2017). Climate scenarios. Lecture at the Winter School in Marine Environmental Prediction, Rimouski (Canada), March 5-10, 2017.
- Grenier P. (2017). Particularités des climats nordiques. Plenary presentation, 7e Symposium Ouranos, Plaza Centre-Ville, Montréal (Canada), November 15-17, 2017.
- Grenier P. (2018). Les changements climatiques dans le nord. Oral presentation, Journée de conférences du Portail sur la recherche nordique et arctique de l'UQAM, Montréal (Canada), February, 8, 2018.
- Brown R., Langen P., Grenier P., Brown R. [Contributing authors: C. Barrette, D. Chaumont, C. Derksen, J. Hamilton, T. Ingeman-Nielsen, S. Howell, T. James, D. Lavoie, S. Marchenko, S. M. Olsen, C. B. Rodehacke, M. Sharp, S. L. Smith, M. Stendel, R. T. Tonboe] (2017). Climate change in the Baffin Bay Davis Strait Region. Arctic Change 2017 conference, Québec (Canada), December 12-15, 2017.
- Chaumont D. (2017). Les scénarios climatiques au Nunavik, Atelier Changements climatiques et transport maritime au Nunavik: vulnérabilité, opportunités et défis d'adaptation. Université de Montréal, Montréal (Canada), July 27, 2017.
- C. Barrette and collaborators are preparing the climate update chapter for the IRIS-4 regional integrated study second iteration. The chapter is an update of climatic trends and variability for the recent past climate over Nunavik and Nunatsiavut as well as an update of the reference and future projected climate (based on results by A. Mailhot, E. Diaconescu, P. Grenier, and D. Dumont).
- P. Grenier, R. Brown, C. Barrette and D. Chaumont contributed to the Adaptation Actions for a Changing Arctic (AACA) Baffin Bay-Davis Strait, report to be published in 2018.
- C. Barrette collaborated to the IRIS-3 process supplying climate information for the greater Hudson Bay terrestrial regions.
- C. Barrette and R. Brown have collaborated to the IRIS-1 climate chapter and were the lead authors for the IRIS-2 climate chapter to be published (spring 2018).
- D. Chaumont and colleagues have collaborated to a project (PAVICS) which consists in a web application tool for providing and visualising climate data to the public. All climate data produced in the current ArcticNet project are/will be accessible through this application. This platform will be operational by end of March 2018.
- Skills and knowledge exchange 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. The paper was published in February 2017 in Discourse web magazine.
- C. Barrette and R. Brown with collaborators contributed to two status reports prepared with the Kativik Regional Government assessing climate trends and variability for the Baie-aux-Feuilles and Cap-Wolstenholme national parks project.

- D. Dumont and C. Sévigny participated to the GreenEdge Amundsen Expedition, during which one wave buoy and a Nortek Aquadopp were successfully deployed on an ice floe in Baffin Bay's marginal ice zone. The objective was to test whether turbulent kinetic energy dissipation could be measuring under the ice through which waves were passing in order to quantify how much wave energy is dissipated by friction. D. Dumont acted as a senior physicist assisting in the planning of the sampling program. He gave multiple lectures on the physics of the marginal ice zone where the expedition was held. This was funded by the GreenEdge project, with in-kind contributions from Ifremer (P. Sutherland).
- D. Dumont traveled to France, at LOPS-Ifremer, to participate in the evaluation committee of Guillaume Boutin's PhD thesis. He gave a lecture entitled "Un observatoire des interactions vagues-glace dans l'estuaire du Saint-Laurent". This trip was funded by Ifremer.
- D. Dumont spent three days at the Canadian Meteorological Centre (Division de recherche en prévision numérique) working with J. F. Lemieux and F. Dupont on sea ice modeling, 9-11 November 2017. He gave a lecture on wave-ice interactions in marginal seas on 10 November.
- A film is being produced on field research activities carried by D. Dumont's team on wave-induced ice break-up and wave-ice interactions in the Bic national Park. This film is done as part of the Plan Large programme of Paraloeil.
- D. Dumont participated as an invited scientist to the programme on Mathematics of Sea Ice Phenomena of the Isaac Newton Institute (September to December 2017), Cambridge University. He gave a lecture entitled Sea ice break-up in the marginal ice zone on 6 December 2017 as part of the workshop Sea Ice Fracture and Cracks (https://www.newton.ac.uk/seminar/20171206100011001).
- Dumont, D. (2017). Wave-ice and seabed-ice interactions, Centre Météorologique Canadien, Dorval, 10 novembre.
- Baudry J., Dumont, D. (2017). Sea Ice Modeling and Data Assimilation Workshop, Montréal, DATE.
- Dugas, S., Dumont, D., Chavanne, C. (2017). Réunion scientifique annuelle Québec-Océan, Rivière-du-loup, 13-14 novembre. (affiche).

INTRODUCTION

Climate indicators in historical and future climate

The Canadian Arctic is a vast region covering approximately 3 600 000 km^2, with a complex topography, a large number of lakes and 94 major islands. Previous studies based on observational data and dedicated to the analysis of past and present climate (e.g. Vincent et al. 2012 and Mekis and Vincent 2011) showed that the Canadian Arctic have experienced warming over the 1950-2010 period at a rate that is about twice the global average. Also, climate change projections realised with coupled global climate models (GCMs) from the Fifth Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) indicate that, for the Canadian Arctic, the actual warming trend will continue over the 21st century with a rate depending on the emission scenario (IPCC 2013). The significant GCM-projected changes over the Arctic will have important impacts on the management, development and conservation of natural resources and especially on the traditional lifestyles of northern Indigenous peoples that are strongly linked to their land and environment (e.g., winter roads on frozen lakes and rivers, migration of caribou herds).

Detailed climate projections are needed at spatial scales much finer than those at which the GCM projections are realized to address the specific climate change issues of these regions. Statistical downscaling strategies or regional climate models (RCMs) integrated over Canadian Arctic can be used to assess future climate changes and assist stakeholder in their evaluation of adaptation strategies. In general, RCMs outperformed GCMs in reproducing spatial distribution and magnitude of present-day precipitation and climate extremes because of their finer resolution that enables a more detailed representation of the topography, the coastlines, the land-surface heterogeneities, and some local small-scale processes (e.g., Kim et al. 2002; Diallo et al. 2012; Paeth and Mannig 2012; Haensler et al. 2013; Lee and Hong 2013; Giorgi et al. 2014; Dosio et al. 2015; Shi et al. 2017; Fotso-Nguemo et al. 2017).

A previous ArcticNet report (Allard and Lemay, 2012) used simulations based on one RCM (OURANOS-CRCM5 model) driven by two GCMs, considering one emission scenario (SRES A2). Since then, the international scientific community has focused on constructing climate projections over many land regions of the globe using RCM ensemble projections through Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative of the World Climate Research Programme (WCRP); Giorgi et al. 2009; Gutowski et al. 2016). The CORDEX framework is based on the set of new GCM simulations from CMIP5, used in the Fifth IPCC Assessment Report, which better sampled GCM related uncertainty. Uncertainty related to natural variability is investigate through different GCM members and the uncertainty in forcing is explored by looking at two emission scenarios (Representative Concentration Pathways – RCPs - RCP 4.5 and RCP 8.5).

The main goal of this part of the project was to provide ArcticNet IRIS-related projects with climate scenarios that benefit from the latest RCM simulations and using the most recent methods. Delivered datasets consist in a large variety of climate indicators based on daily temperature, precipitation and snow depth. They complete those used in previous reports (Allard and Lemay 2012; Stern and Gaden 2015) with new ones that focus on extremes, selected from the Expert Team on Climate Change Detection and Indices (ETCCDI; Klein Tank et al. 2009) list.

Post-processing methods

Statistical post-processing (SPP) of simulations from numerical climate models aims at producing plausible future climate trajectories, by removing possible biases and/or rescaling them. Many SPP techniques exist, among which is the quantile mapping (QM) approach. QM is widely used for producing climate scenarios at the daily time scale (Maraun 2016). The central idea of QM is to determine the transfer function that represents the mismatch between a simulated time series and a reference product during a calibration period, and to apply this transfer function to the whole time series. Such a technique is relatively simple to apply, but numerous problems have been pointed out in the literature (e.g., Hewitson 2014). First, the technique is not physically-based, so there are concerns that its output may be physically inconsistent. Secondly, the technique may be applied with different levels of sophistication, involving a range of parameters and options whose impacts are not well known, especially on less investigated variables such as wind and humidity. Moreover, QM has been often applied on variables like wind and humidity, unlike temperature and precipitation, and QM performance for such variables remains unknown.

In this project, the QM technique has been thoroughly investigated using Arctic or sub-Arctic test sites. First, potential physical inconsistency has been classified in different types and investigated in terms of frequency of occurrence and amplitude, and different strategies, *a priori* conceivable for avoiding such problems, have been compared. Secondly, the impact of several parameters (e.g., the width of the moving window for defining the transfer function) and options (e.g., preservation of the long-term simulated trend, multivariate treatment) have been investigated. Thirdly, the impact of QM on several statistical properties (e.g., diurnal cycle, annual cycle) of simulated time series has been investigated for wind components, relative humidity, specific humidity and pressure. The investigation has not been made separately for the three points listed above, but rather often performed in an integrated way, for example by investigating the issue of physical consistency between relative humidity and related variables (temperature, pressure, specific humidity) in scenarios for Iqaluit and Yellowknife. Overall, the multiple case studies involving various northern sites and regions led to many improvements to the QM algorithm used for generating daily climate scenarios, and to shed light on the different strategies available to avoid inter-variable physical inconsistency.

Development of scenarios combining reference datasets

Defining a reference climate is an important issue for climate change impacts and the development of adaptation strategies. This remains a challenge in regions that were historically poorly covered by meteorological stations such as Northern Canada.

Reanalyses represents an interesting alternative for such regions as they provide comprehensive and consistent spatio-temporal gridded datasets. Reanalyses consist of a background forecast model and data assimilation routine that combines available observational datasets with model forecast to generate uniform gridded datasets (Bosilovich et al. 2008). They have been widely used in different climate research applications (e.g. Alexeev et al. 2011; Zou et al. 2014; Lindsay et al. 2014). Extreme indices for precipitation and temperature from reanalysis have also been used as references for the evaluation of climate models (e.g., Sillmann et al. 2013). Their consistency with global gridded observational datasets have been verified (Donat et al. 2014), showing improvements in representation of the spatial patterns after 1979 when satellite data were included in the assimilation process.

Despite their overall good spatio-temporal representation of many variables, some of them, for example precipitation, are still not well represented in some regions, mainly because observational datasets for these variables have not been explicitly used in the assimilation process (Saha et al. 2010; Dee et al. 2011; Kobayashi et al. 2015; Rienecker et al. 2011). Evaluating daily climate indices over the northern parts of Canada, Diaconescu et al. (2017) recommend caution when using extreme daily precipitation indices from reanalyses as reference datasets for these regions. Reanalyses therefore need to be post-treated or bias corrected before they could be used. Their performances depend on the variable considered, the data assimilation routine, the assimilated observational datasets, and the forecast model (Lorenz et al. 2012).

One possible option for improving the representation of reference climate is through the correction of reanalysis datasets with in situ observations through data assimilation methods. These methods combine model fields with observational datasets to create an improved model dataset (Kalnay 2002; Bertino et al. 2007). It can be incorporated into the modeling process through two different forms: in online mode, which increase the quality of the initial conditions sequentially for new model simulations and in off-line mode, which is used to create the best estimation once the entire period is simulated, combining model outputs with observational data (Candiani et al. 2013; Matsikaris et al. 2015).

The off-line mode was applied using the Optimal Interpolation (OI) and Ensemble Optimal Interpolation (EnOI) methods. OI was applied to each reanalysis independently and EnOI to all reanalyses combined. Both methods are quite similar, their main difference being in how the background error covariance is defined (Ren and Hartnett 2017). OI method have been used to merge different sources of precipitations in some regions of the world (e.g., Häggmark et al 2000; Mahfouf et al. 2007; Soci et al. 2016). Furthermore, significant improvements were obtained with its application at global scale by Nie et al. (2016) merging satellite information with observations and model predictions.

The objective of part of the project is to develop a reference dataset for some precipitation indicators for Canada. Two data assimilation methods, Optimal Interpolation (OI) and Ensemble Optimal interpolation (EnOI) methods, were used to combine four reanalysis datasets (CFSR, Era-Interim, JRA55 and MERRA) with observations. A total of 2160 meteorological stations with minimally 10-year precipitation records were used. Annual values of ten Climate Precipitations Indices (CPI) covering a 30-year period (1980-2009) were estimated for each dataset and were then combined (reanalysis + observations) to improve the representation of each climate indicator across Canada. A cross-validation strategy was finally applied and to test the performance of the proposed reference at sites where no recorded precipitations are available. The proposed dataset was also compared to the gridded observational dataset from Natural Resources Canada (NRCan; McKenney et al. 2011).

Modeling of wave and fast ice dynamics in Baffin Bay and Hudson Bay

Coastal communities of the Canadian Arctic are tremendously dependent upon the marine environment. It brings food, allows transportation and defines their culture. In a context of climate change, however, the risks associated with marine hazards are likely to change, making them more difficult to evaluate and predict. Coastal erosion, or more generally coastal morphologic changes, is most of the time caused by waves. During winter, sea ice prevents wave generation and contributes to attenuate waves that would be generated in ice-free regions propagating towards ice-covered regions, such that erosion or hazardous sea states happen mostly during the ice-free summer season, during which winds are generally weaker.

Global warming is very likely to change that situation by shortening the period during which sea ice protects the coast from stronger winter winds. This phenomenon has already been documented in the Gulf of St. Lawrence by Ruest et al. (2015), who used empirical methods for estimating the extreme wave climate and the effect of sea ice on it. One of their conclusions is that sea ice can be neglected if one wants to estimate long-term statistics of wave by the end of the 21st century. Although this method is valuable for evaluating first order effects of sea ice on the wave climate over a large area, it is not comparing to the latest knowledge about wave-ice physics and it can't reasonably be applied for coastal locations.

The current part of the project aimed at including the latest knowledge about wave-ice interactions, developed by Dumont and his collaborators (Dumont et al. 2011, Williams et al. 2013a, 2013b), into state-of-the-art numerical models and use them to perform ensembles of sea ice and wave climate simulation covering the recent past and future periods (1980-2100). These simulations were forced by scenarios of the state of the atmospheric (wind and temperature) produced by Ouranos during this project.

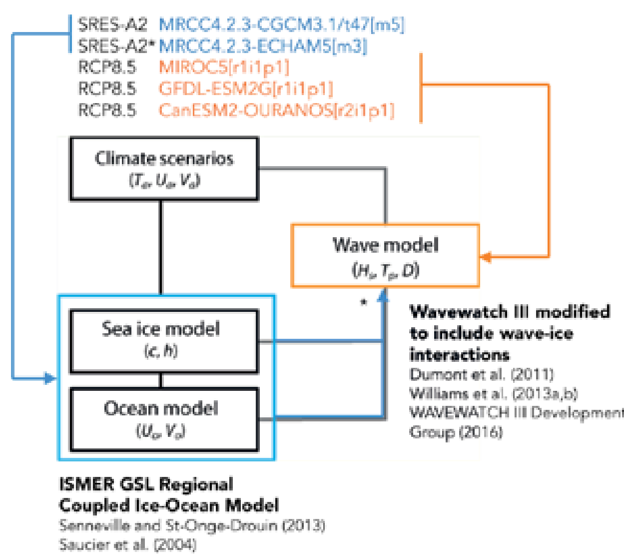


Figure 1. Schematic showing the atmospheric, coupled ice-ocean and wave model simulations realized during the project and their dependencies.

Table 1. Coastal climate indicators related to sea ice and waves. Each indicator can be either estimated at the basin scale or at the local scale (stations) unless specified otherwise.

Type of indicator	Indicator	Unit
Sea ice	Maximal annual ice coverage	%
	Ice freeze-up date (> 30%)	day of year (DOY)
	Ice melt onset date (< 30%)	day of year (DOY)
	Daily average ice coverage	%
	Daily averaged mean ice thickness	m
Wave	2- and 10 year return significant wave height	m (at stations only)
	Annual mean significant wave height	m
	Winter mean significant wave height	m
Wave-ice	Start, end and duration of the safe period	day of year (DOY)
	Mean ice thickness during safe period	m
	Mean critical ice thickness	m

Figure 1 depicts the modeling tools and strategy used to compute coastal climate indicators (Table 1). Two atmospheric climate scenarios were used to force two coupled ice-ocean model simulations using ISMER's GSL Regional Coupled Ice-Ocean Model (Saucier et al. 2004; Senneville and St-Onge-Drouin 2013). One of these simulations (MRCC4.2.3-ECHAM5[m3]-ISMER-GSL) was used to provide sea level, currents and ice parameters to WAVEWATCHIII, which was forced by three different RCP8.5 regional climate scenarios. This exercise is the first ever to be completed in Canada, and one of the first in the world.

Table 1 shows the eleven (11) coastal climate indicators that were defined and chosen for characterizing the reference climate and climate change. These climate indicators are relevant for a broad range of potential users. Extreme wave height was also considered as a relevant indicator for coastal erosion and risk for infrastructures. In order to complement sea ice indicators, which traditionally focus on the amount of ice (concentration and thickness), indicators related to ice resistance to wave-induced break-up were also considered. The concept of a safe period was therefore defined, which refers to the period during which sea ice is not broken-up by waves. It means either that sea ice is thick enough to resist waves, and/or that waves are not energetic enough to break-up the ice. Because of this highly non-linear and non-local relationship between waves and sea ice, such an indicator can't easily be evaluated without a coupled numerical model simulating these processes as the one used in this study.

ACTIVITIES

The following ArcticNet funded activities (and related) activities were carried out during the 2017-2018 fiscal year:

- Two coordination meetings took place during 2017-2018. The first one was held at the Institut des Sciences de la Mer (ISMER) on May 24, 2017 and the second one was held at the Ouranos office in Montréal on November 14, 2017. These were the 4th and 5th coordination meetings of the project. During these meetings, each collaborator and his team were invited to present a summary of their works. An update of the recent activities related to the project as well as planned activities is also made.

- All climate indicators were submitted to C. Barrette in order to be included in the IRIS-4 Climate chapter and in the Climate Atlas to be prepared. The graphical items include reference climate and projection maps, time series and boxplots. The indicators were calculated for air temperature, precipitation, snow depth, wind, waves, sea ice and the sea-ice safe period.
- Several key regional sites were identified in the prior phases of the project and simulation results were made available for each site.
- In addition to the reference and projection climate information supplied for the IRIS-4 climate chapter, climate variability and trend analysis were produced with the support of R. Brown and R. Way at a regional scale. Sea-ice freeze-up and melt-off trend analysis for the Hudson Bay, Hudson Strait and Labrador Sea were also provided by S. Howell and are included in the Climate chapter.
- All files about the projected climate were supplied to the Ouranos team in early January 2018 and will be included in the PAVICS platform. All datasets are publicly available.

RESULTS

Results have been organized in term of the main topics of the study: 1. Climate indicators in historical and future climate; 2. Post-processing methods; 3. Development of scenarios combining reference datasets; 4. Modeling of wave and fast ice dynamics in Baffin Bay and Hudson Bay.

Climate indicators in historical and future climate

Gathering of the most recent regional climate simulations and recent datasets combining reanalysis and observational datasets

This milestone aimed at gathering available regional climate simulations that cover the Canadian Arctic (IRIS-1 and IRIS-2 domains) and the Canadian Subarctic (IRIS-3 and IRIS-4 domains). Regional climate simulations from two projects that were part of the Coordinated Regional Downscaling Experiment (CORDEX; for details see Giorgi et al. 2009; Jones et al. 2011; Gutowski et al. 2016) were used, namely the Arctic CORDEX and the North America (NA) CORDEX projects. Figure 2 shows the inner domains of integration used by the majority of models participating in these two CORDEX projects. The Arctic CORDEX covers the Canadian Arctic (IRIS-1 and IRIS-2 domains), while the NA CORDEX covers the Canadian Subarctic (IRIS-3 and IRIS-4 domains).

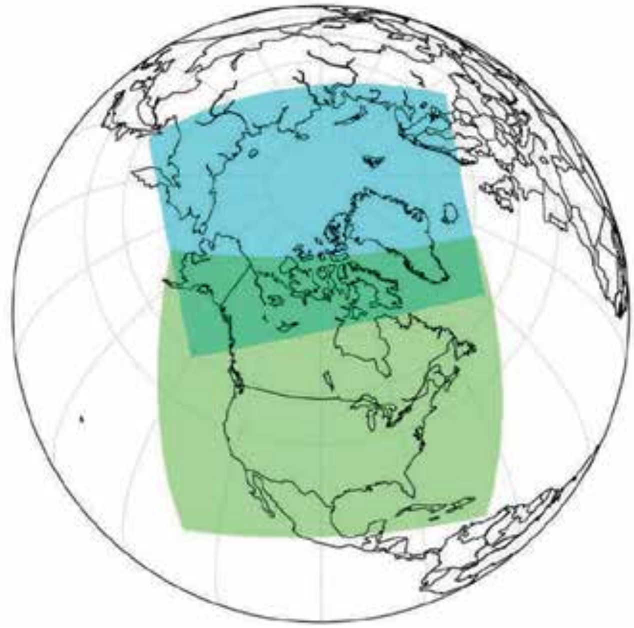


Figure 2. Inner domain of integration for ARCTIC CORDEX simulations (in cyan) and for NA CORDEX simulations (in olive green). The common region is shown in emerald green.

The Regional Climate Model (RCM) simulations include historical runs and projections based on two Representative Concentration Pathways (RCPs; van Vuuren et al. 2011):

- RCP 4.5 is a medium-low emission scenario that corresponds to a radiative forcing peaking at 4.5 Wm^{-2} (≈ 650 ppm CO_2 equiv.) by 2100.
- RCP 8.5 is a high emission scenario in which the increasing greenhouse gas emissions lead to a radiative forcing pathway of 8.5 Wm^{-2} (≈1370 ppm CO_2 equiv.) by 2100.

RCMs are driven by coupled climate model simulations from the Fifth Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012). The historical data range is from 1951 to 2005, while

Table 2. The four ensembles of simulations used in the study. Simulation names are structured as Institution-RCM-GCM-CORDEX experiment.

RCP	Arctic ensemble (IRIS-1 and IRIS-2) (Institution-RCM-GCM-experiment)[1,2]	Subarctic ensemble (IRIS-3 and IRIS-4) (Institution-RCM-GCM-experiment)[1,2]
4.5	CCCma-CanRCM4-CanESM2-ARC-0.22 DMI-HIRHAM5-EC-EARTH-ARC-0.44 OURANOS-CRCM5-CanESM2-NA-0.22 SMHI-RCA4-CanESM2-ARC-0.44 SMHI-RCA4-EC-EARTH-ARC-0.44 SMHI-RCA4-MPI-ESM-LR-ARC-0.44 SMHI-RCA4-NorESM1-M-ARC-0.44 UQAM-CRCM5-CanESN2-NA-0.44 UQAM-CRCM5-MPI-ESM-LR-NA-0.44	CCCma-CanRCM4-CanESM2-NA-0.22 DMI-HIRHAM5-EC-EARTH-NA-0.44 OURANOS-CRCM5-CanESM2-NA-0.22 SMHI-RCA4-CanESM2-NA-0.44 SMHI-RCA4-EC-EARTH-NA-0.44 UQAM-CRCM5-CanESN2-NA-0.44 UQAM-CRCM5-MPI-ESM-LR-NA-0.44
8.5	AWI-HIRHAM5-MPI-ESM-LR-ARC-0.44* CCCma-CanRCM4-CanESM2-ARC-0.22 DMI-HIRHAM5-EC-EARTH-ARC-0.44 MGO-RRCM_MPI-ESM-LR-ARC-0.44 OURANOS-CRCM5-CanESM2-NA-0.22 SMHI-RCA4-CanESM2-ARC-0.44 SMHI-RCA4-EC-EARTH-ARC-0.44 SMHI-RCA4-MPI-ESM-LR-ARC-0.44 SMHI-RCA4-NorESM1-M-ARC-0.44 UQAM-CRCM5-CanESN2-NA-0.44 UQAM-CRCM5-MPI-ESM-MR-NA-0.44	CCCma-CanRCM4-CanESM2-NA-0.22 DMI-HIRHAM5-EC-EARTH-NA-0.44 IowaState-RegCM4-GFDL-ESM2M-NA-0.22* IowaState-RegCM4-HadGEM2-ES-NA-0.22* NCAR-RegCM4-MPI-M-MPI-ESM-LR-NA-0.22* OURANOS-CRCM5-CanESM2-NA-0.22 SMHI-RCA4-CanESM2-NA-0.44 SMHI-RCA4-EC-EARTH-NA-0.44 UArizona-WRF-GFDL-ESM2M-NA-022* UQAM-CRCM5-CanESN2-NA-0.44 UQAM-CRCM5-MPI-ESM-MR-NA-0.44

1. ARC-0.22: Arctic CORDEX simulations with 0.22 degree of spatial resolution; ARC-0.44: Arctic CORDEX simulations with 0.44 degree of spatial resolution; NA-0.22: NA CORDEX simulations with 0.22 degree of spatial resolution; NA-0.44: NA CORDEX simulations with 0.44 degree of spatial resolution.

2. An asterisk (*) after a simulation name indicates that only daily minimum temperature, daily maximum temperature, daily mean temperature and daily total precipitation were available for this simulation (no daily solid precipitation or daily snow depths available).

the projections range from 2006 to 2100. Table 2 shows the RCM ensembles of simulations.

Two RCMs participating in NA CORDEX are integrated over a larger domain than the NA-CORDEX domain presented in Figure 2: UQAM-CRCM5 and Ouranos-CRCM5. Since these entirely cover Canada, they were used for both the Arctic and the Subarctic regions. With the exception of RCP 8.5 Ouranos-CRCM5-CanESM2-NA-0.22, all simulations are made up of a unique combination of regional and global models. For RCP 8.5 Ouranos-CRCM5-CanESM2-NA-0.22, five simulations were available, each driven by a different member of the CanESM2 global ensemble.

Four RCM ensembles were therefore considered:

- RCP 4.5 ensemble for the IRIS-1 and IRIS-2 domains (9 simulations)

Table 3. Datasets used to asses RCM performance and to define the reference climate.

Dataset acronym (Reference)	Description (spatial resolution)
ERA-Interim (Dee *et al*. 2011)	European Center for Medium-Range Weather Forecast Reanalysis (~ 79 km)
MERRA for temperature and precipitation indicators and MERRA2 for snow depth indicators (Rienecker *et al*. 2011)	Modern-Era Retrospective Analysis for Research and Application MERRA and MERRA2 are two versions of the same NASA reanalysis (~ 65 km)
JRA-55 (Kobayashi *et al*. 2015)	55-year Japanese Reanalysis (~ 60 km)
CFSR (Saha *et al*. 2010)	Climate Forecast System Reanalysis and Reforecast (~ 38 km)
GMFD (Sheffield *et al*. 2006)	Global Meteorological Forcing Dataset for land surface modeling; produced by Princeton University and based on the NCEP-NCAR reanalysis, combined with a suite of global observation-based data including CRU monthly climate variables, GPCP daily precipitation, TRMM3B42 3-hourly precipitation satellite product, and NASA Langley Research Center monthly surface radiation budget (0.25°).
WFDEI (Weedon *et al*. 2014)	WATCH (WATer and global CHange) Forcing Data methodology applied to ERA-Interim; uses GPCC precipitation dataset (0.5°).
AgCFSR (Ruane *et al*. 2015).	NASA dataset combining CFSR with observational datasets from *in situ* observational networks and satellites (CRU, TRMM, CMORPH, and PERSIANN) (0.25°)
AgMERRA (Ruane *et al*. 2015).	NASA dataset combining MERRA (or MERRA-Land for precipitation) with observational datasets from *in situ* observational networks and satellites (CRU, TRMM, CMORPH, and PERSIANN) (0.25°)
Pan-Arctic Reconstruction (Liston and Heimstra 2011)	Snow cover reconstruction using the physical snowpack model SnowModel driven by 10 km downscaled atmospheric fields from MERRA; SnowModel is designed for Arctic snow cover (e.g., takes into account blowing snow sublimation losses) but offer only a partial coverage of the IRIS 4 region (north of about 56°N) (10 km).
Blended5 (Mudryk *et al*. 2015).	Average of five daily snow water equivalent (SWE) datasets: GlobSnow, ERA-Interim Land, MERRA, Crocus model (driven by ERA-Interim meteorology), and GLDAS-2 land data assimilation product (1°).

- RCP 8.5 ensemble for the IRIS-1 and IRIS-2 domains (11 simulations)
- RCP 4.5 ensemble for the IRIS-3 and IRIS-4 domains (7 simulations)
- RCP 8.5 ensemble for the IRIS-3 and IRIS-4 domains (11 simulations)

Eight reanalyses-based datasets with relevant spatio-temporal resolutions were identified as potential candidates to define the reference climate for temperature and precipitation indicators. For snow-depth indicators, however, only four databases providing daily snow-depth are available. Table 3 presents these datasets and their main characteristics.

Estimation and comparison of climate indicators in observational datasets and simulations, and selection of the datasets defining the reference climate

Assessment of RCM performance in simulating a large variety of climate indicators for the present-day Arctic conditions and development of a reference climate for these regions was carried out. Relevant climate indicators were identified and validated by the stakeholders and consist in: 21 temperature-related indicators (Table 4); 12 total precipitation-related indicators (Table 5); 9 liquid and solid precipitation-related indicators (Table 6); 5 snow depth-related indicators (Table 7). Five wind-related indicators were also considered: annual average of daily average wind; annual average of daily maximum wind; annual maximum daily maximum wind; number of days for which maximum wind speed exceeds force 6 (39 km/h) on the Beaufort scale.

All climate indicators were computed for each of these simulations except for the Ouranos simulations where the median of the five simulated indicator values was considered in the RCM multi-model ensemble. Since some simulations used a 0.22° grid while others used a 0.44° grid, simulation with the finest spatial resolution were used for the multi-model ensemble.

Since Canadian Arctic and Subarctic regions are poorly covered by meteorological networks, and because the quality of the interpolated datasets is highly dependent on network density, the assessment of the reference climate was done by comparing all the available gridded datasets to station records. Daily precipitation, mean maximum and minimum temperature records from Environment and Climate Change Canada (ECCC) DAI Portal and from the Adjusted and Homogenized Canadian Climate Data (AHCCD; Vincent et al. 2012, Mekis and Vincent 2011) were used to estimate temperature and precipitation indicators, while station records of daily snow depths from the Canadian Meteorological Centre (CMC; Brown and Brasnett 2010) were used for the snow-depth indicators. The reference climate is defined as the 1980-2004 period.

Assessment of the relative performance of available datasets (Table 3) and RCM CORDEX ensemble (Table 2) in simulating precipitation and temperature over IRIS-1 and IRIS-2 regions for the reference period was first carried out. The detailed results of this analysis are presented in Diaconescu et al. (2017). The performance over the IRIS-4 domain was then evaluated. The evaluation was done by comparing the mean indicators over the reference period on each native grid point of each dataset presented in Table 3 to the corresponding values at the closest stations. The median of the RCM ensemble was also considered in the analysis (the median was obtained after models were interpolated on a common grid with a spatial resolution of 0.25°). A large variety of metrics was used to assess dataset performance. Figure 3 summarises the results for the IRIS-4 region in terms of the normalised root mean square differences (NRMSD), defined as the sum of the squared differences between the mean indicator value over the 1980-2004 period at a grid-point of a given dataset and the corresponding value at the closest station over all grid-point/stations pairs belonging to the IRIS-4 region (see Diaconescu et al. 2017). Normalization factor is given by the difference between the largest and the smallest climate mean values over all stations. A NRMSD value of zero means a perfect agreement

Table 4. Temperature-related climate indicators considered in the study.

Acronym (units)	Name	Definition
Annual mean T (°C)	Annual mean temperature	Annual average of daily mean temperature (Tmean)
DJF mean T (°C)	Winter (DJF) mean temperature	December, January and February (DJF) average daily mean temperature (Tmean)
JJA mean T (°C)	Summer (JJA) mean temperature	June, July and August (JJA) average daily mean temperature (Tmean)
ID (days)	Number of freezing days	Number of days with daily maximum temperature below 0°C (Tmax < 0°C), over a winter-centred year (from July to June)
Nthaw (days)	Winter thaw events	Number of days with daily maximum temperature above 0°C (Tmax > 0°C) during winter period (winter period is delimited by the two dates when the 40-day centred moving average of daily mean temperature crossed -5°C)
TDD (degree days)	Thawing Degree Days	Cumulative sum of daily mean temperature above 0°C, over a calendar year (from January to December)
FDD (degree days)	Freezing Degree Days	Cumulative sum of daily degrees of daily mean temperature below 0°C, over a winter-centred year (from July to June)
HDD (degree days)	Heating Degree Days	Cumulative sum of daily degrees of daily mean temperature below 17° C, over a winter-centered year (from July to June)
GDD (degree days)	Growing degree days	Cumulative sum of daily degrees of daily mean temperature above 5°C, over a calendar year (from January to December)
SSD (calendar days)	Summer Start Day	First calendar day (from January to December) when the 10-day centered moving average of daily minimum temperature crosses the 0°C value
SED (calendar days)	Summer End Day	First calendar day (from January to December) after August 1st, when the 10-day centered moving average of daily minimum temperature crosses the 0°C value.
SSL (days)	Summer season length	Number of days between Summer End Day and Summer Start Day
TNn (°C)	Annual coldest temperature	Annual minimum value of daily minimum temperature
TN10 (°C)	Extreme cold nights	10th percentile of daily minimum temperature over the calendar year (from January to December)
TX10 (°C)	Extreme cold days	10th percentile of daily maximum temperature over the calendar year (from January to December)
TN10p (%)	Frequency of cold nights	Annual percentage of days with daily minimum temperature smaller than the 10th percentile of daily minimum temperature over the period of reference 1980-2004
TX10p (%)	Frequency of cold days	Annual percentage of days when daily maximum temperature is smaller than the 10th percentile of daily maximum temperature over the period of reference 1980-2004
TXx (°C)	Annual warmest temperature	Annual maximum value of daily maximum temperature
TX90 (°C)	Extreme warm days	90th percentile of daily maximum temperature over the calendar year (from January to December)
TX90p (%)	Frequency of warm days	Annual percentage of days with daily maximum temperature greater than the 90th percentile of daily maximum temperature over the period of reference 1980-2004
TN90p (%)	Frequency of warm nights	Annual percentage of days with daily minimum temperature greater than the 90th percentile of daily minimum temperature over the period of reference 1980-2004

Table 5. Climate and extreme total precipitation indicators.

Acronym (Units)	Name	Definition
Annual mean Pr (mm/day)	Annual mean precipitation	Annual mean of daily precipitation
DJF mean Pr (mm/day)	Winter Mean precipitation (DJF)	December, January and February (DJF) average of daily precipitation
JJA mean Pr (mm/day)	Summer Mean precipitation (JJA)	June, July and August (JJA) average of daily precipitation
R1mm (days)	Wet days	Annual number of days with daily precipitation ≥ 1 mm/day
RX1day (mm/day)	Annual maximum 1-day precipitation	Annual maximum of daily precipitation
RX5day (mm/day)	Annual maximum 5-day precipitation	Annual maximum of 5-day accumulated precipitation
PR95 (mm/day)	95th percentile of daily precipitation	95th percentile of daily precipitation over all days of the year
PR99 (mm/day)	99th percentile of daily precipitation	99th percentile of daily precipitation over all days of the year
R95pTOT (mm)	Precipitation due to very wet days	Annual sum of daily precipitation during days with daily precipitation greater than the 95th percentile of wet-day precipitation over the reference period (1980-2004)
R99pTOT (mm)	Precipitation due to extremely wet days	Annual sum of daily precipitation during days with daily precipitation greater than the 99th percentile of wet-day precipitation over the reference period (1980-2004)
R95p (days)	Very wet days	Annual number of days with daily precipitation greater than the 95th percentile of wet-day precipitation over the reference period (1980-2004)
R99p (days)	Extremely wet days	Annual number of days with daily precipitation greater than the 99th percentile of wet-day precipitation over the reference period (1980-2004)

Table 6. Liquid and solid precipitation-related indicators.

Acronym(Units)	Name	Definition
Annual mean Prsn (mm/day)	Annual mean solid precipitation	Annual mean of daily solid precipitation
Annual FRSN	Annual fraction of solid precipitation	Fraction of the total annual precipitation in the form of solid precipitation
PL1mm (days)	Number of winter rainfall	Number of days with daily liquid precipitation during the winter period (winter period is delimited by the two dates when the 40-day centered moving average of daily mean temperature crossed -5°C)
PLTOT (mm)	Total winter rainfall	Sum of liquid precipitation during the winter period (winter period is delimited by the two dates when the 40-day centered moving average of daily mean temperature crossed -5°C)
RX1day Snow (mm/day)	1-day maximum snowfall	Annual maximum of daily solid precipitation in a winter-centred year (from August to July)
Snow 2-year return level (mm/day)	Snow 2-year return level	Annual maximum of daily solid precipitation with 2-year return period
Snow 5-year return level (mm/day)	Snow 5-year return level	Annual maximum of daily solid precipitation with a 5-year return period
Snow 10-year return level (mm/day)	Snow 10-year return level	Annual maximum of daily solid precipitation with a 10-year return period
Snow 20-year return level (mm/day)	Snow 20-year return level	Annual maximum of daily solid precipitation with a 20-year return period

Table 7. Snow-depth related indicators.

Acronym (Units)	Name	Definition
SDmax (m)	Maximum snow depth	Maximum snow depth during a winter-centred year (from August to July)
DSDmax (number of days from August 1st)	Date of maximum snow depth	Date of occurrence of the maximum snow depth during a winter-centered year (from August to July)
SDCSC (number of days from 1st August)	Start date of continuous snow cover	First day of the 14 consecutive-day period with snow depths ≥ 2 cm for a winter-centered year (from August to July)
EDCSC (number of days from 1st August)	End date of continuous snow cover	First day after the SDCSC, when the snow depth < 2 cm for 14 consecutive days for a winter-centred year (from August to July)
SCD (days)	Snow cover duration	Annual number of days in a winter-centred year (from August to July) with snow depths ≥ 2 cm

between mean indicator values from the considered dataset and the corresponding station values at all station sites.

Figure 3 shows that the four datasets corrected with observations (GMFD, WFDEI, AgCFSR, and AgMERRA) have the smallest median NRMSD values for temperature and total-precipitation indicators. Interquartile ranges (IQR) of NRMSD values differ from one dataset to the other. AgMERRA has the closest to zero IQR, while NRMSD distributions for GMFD, WFDEI, and AgCFSR display large upper

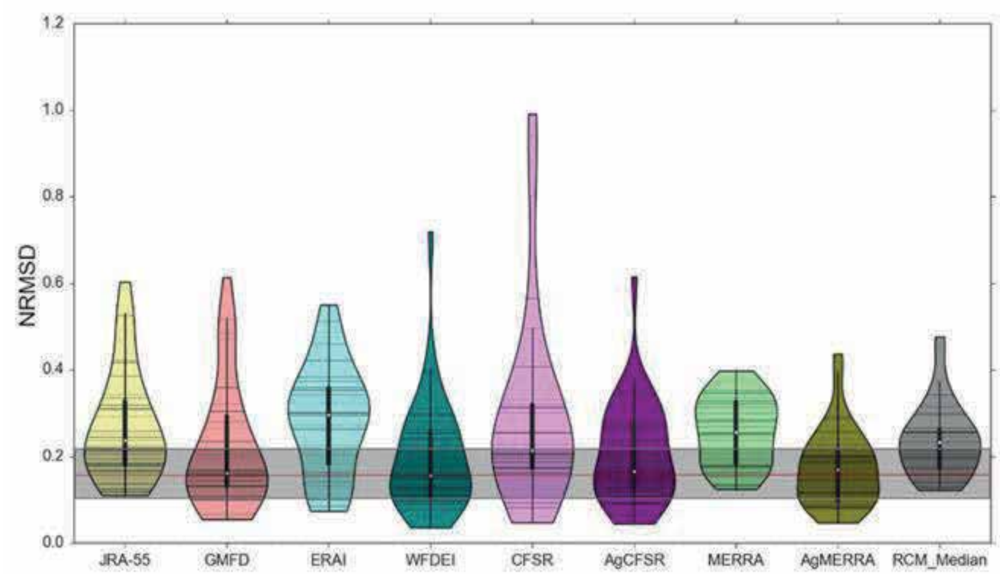


Figure 3. Distribution (violin plots) of normalised root mean square differences (NRMSD) for the 33 temperature and total-precipitation indicators (Tables 4 and 5). Each horizontal line in violin plots corresponds to a NRMSD value for a given indicator for this specific dataset. The box plot within each violin plot defines the interquartile ranges (IQR; grey bars) and 1.5 IQR (whiskers). The red horizontal line is the median value of the dataset with the lowest median NRMSD value (here WFDEI). Grey rectangles along the red line correspond to the closest to zero IQR (here AgMERRA).

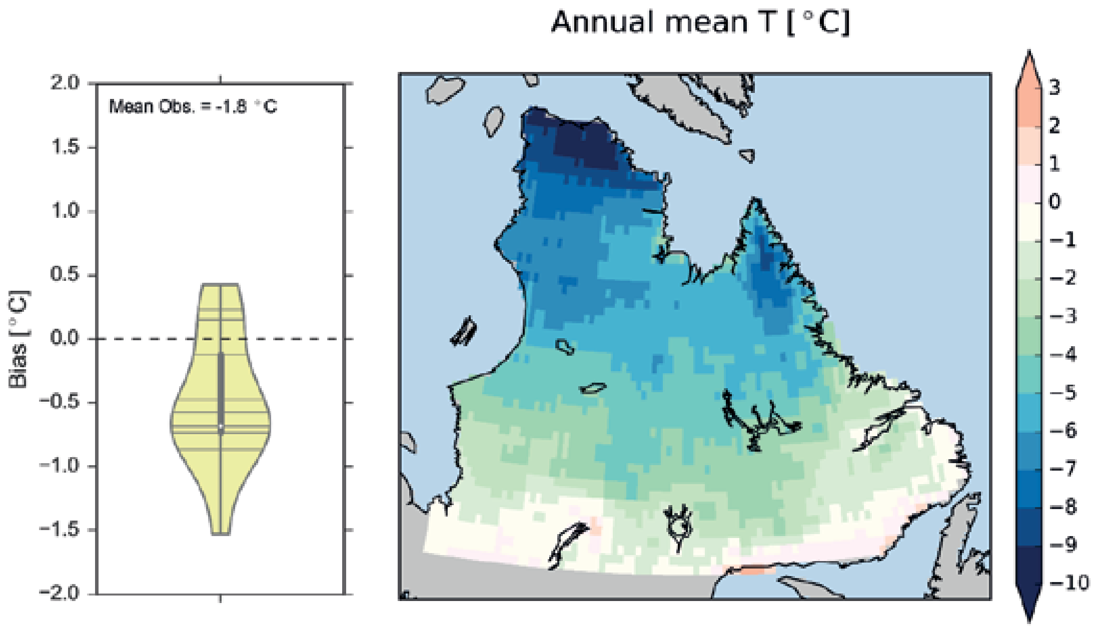


Figure 4. Reference climate (1980-2004) for annual mean temperature (AgMERRA dataset). The violin plot on the left-hand side shows the biases between stations and closest AgMERRA grid-point values for all station/grid point pairs included in the domain. The value appearing above the violin plot corresponds to the mean observed values over all stations included in the domain. Horizontal line in each violin plot corresponds to the bias for one specific grid-point/station pair.

tails. The RCM median (noted RCM_Median) has an NRMSD distribution close to AgMERRA, with a small shift toward higher values, but a smaller IQR. Because AgMERRA has the smallest IQR, it was selected to represent the reference climate for all indices based on temperature and total precipitation.

Following a similar procedure as the one previously described for temperature and total precipitation indicators, MERRA was selected to define the reference climate for liquid and solid precipitation indicators (Table 6) and MERRA2 was selected for snow-depth indicators (Table 7).

Results for all indicators were summarized through maps. Figure 4 presents an example for the reference climate of the annual mean temperature. It shows that the reference climate is characterised by annual temperatures of around -10°C in the north and close to 0°C on the south-east coast. In order to account for uncertainties and biases in the selected reference climate dataset, the distribution of biases (illustrated by violin plots) between stations and closest grid point values over all station/grid point pairs within the domain is also presented. Similar figures were produced for all climate indicators (Tables 4, 5, 6 and 7).

Comparison and selection of a post-processing method to be used for the development of climate projections

The third objective aimed at comparing some post-processing methods proposed in the literature and to select the one that will be used for the construction of climate scenarios over the IRIS-4 region. Several post-processing methodologies were evaluated:

- Simple bias correction of the climate mean
- Quantile mapping of RCMs precipitation and temperature daily series using reference climate values

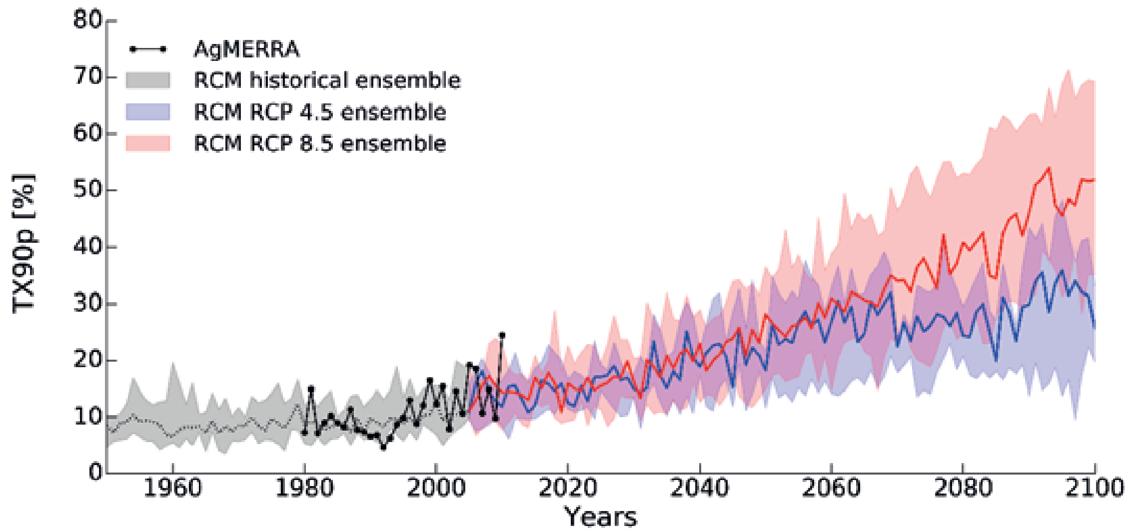


Figure 5. Time series of annual frequency of warm days (TX90p; see Table 4) values averaged over the IRIS-4 region. The blue zone corresponds to the RCP 4.5 ensemble of RCM simulations from 2006 to 2100, while the central blue line shows the corresponding median value. The red zone corresponds to the RCP 8.5 ensemble of RCM simulations from 2006 to 2100 with the median value represented by the red line. The gray zone corresponds to the historical RCM ensemble of simulations from 1950 to 2005 with the median represented by the black dotted line. Each RCM simulation was corrected to have the same 1980-2004 mean value as the reference climate (the black line).

- Quantile mapping of precipitation and temperature daily series of RCMs using many reanalyses

Results showed that the post-processing depends drastically on the quality of the reference climate used to correct the RCM simulations. The assessment of RCM climate indicators over the historical period (1980-2004) showed that the RCM median has biases slightly higher than the AgMERRA dataset, the dataset selected for the reference climate of temperature and precipitation indicators (Figure 3). Consequently, a simple bias correction of the climate mean of each indicator and each RCM was done to develop the climate scenarios over the 1950-2100 period for the IRIS-4 domain. The Delta method (based on the difference in mean values between two future and reference periods) was then used to estimate the projected changes over the two future periods. Figure 5 presents an example of the annual time series for the TX90p indicator (Table 4) averaged over IRIS-4, once biased corrected. Each RCM simulation was corrected to have the same 1980-2004 mean as the reference climate. Similar figures for all climate indicators were generated.

Development of climate projections for all indicators for two future periods (2040-2064 and 2076-2100) and two radiative forcing scenarios (RCP 4.5 and RCP 8.5)

Two 25-year future periods were considered for climate change projections. One is centered on the mid-century (2040-2064) and the other one considers the end of the century (2076-2100). Changes between these future periods and the reference period were estimated, for a given climate indicator, by subtracting the mean indicator value over the future period to the corresponding mean value over the reference period. Such changes were computed for each climate indicator, at each grid point of every RCM simulations and for the two emission scenarios (RCP 4.5 and RCP 8.5).

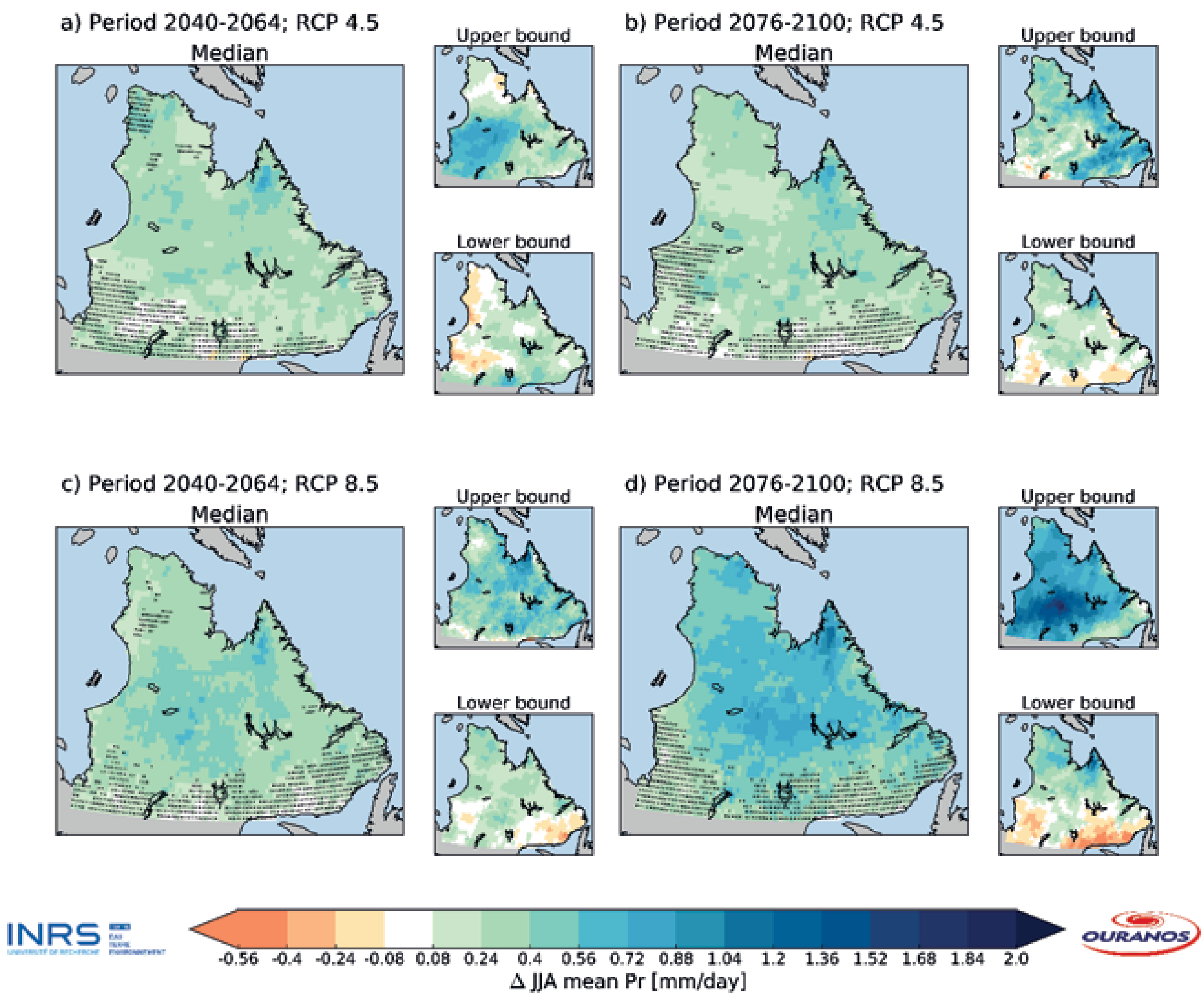


Figure 6. Climate-mean differences between the future periods and the reference period (1980-2004) for June-July-August (JJA) mean precipitation (Δ JJA mean Pr) for two climate scenarios: a) period 2040-2064, RCP 4.5; b) period 2076-2100, RCP 4.5; c) period 2040-2064, RCP 8.5; d) period 2076-2100, RCP 8.5. Central maps of each panel (a, b, c, and d) show the median of the simulated differences at each grid-point. Grid points where at least 10% of simulation disagree on the sign of change (positive or negative) are indicated with an 'x'. Grid points without 'x' mean that at least 90% of simulations project a climate change of the same sign as the median. The two secondary maps next to each central map give an indication on the dispersion of projected changes: 'Upper bound' shows the simulation with the greatest mean changes over the domain, while 'Lower bound' shows the simulation with the smallest mean changes over the domain.

Maps of the projected changes over the IRIS-4 region were produced. Figure 6 presents an example of such map for the June-July-August (JJA) mean precipitation (Pr) indicator. Each panel shows the median change at each grid point and 'upper bound' and 'lower bound' corresponds to the simulation with the largest and smallest mean regional climate change. This figure shows, for instance, that June-July-August (JJA) mean precipitation will increase in the northern part of Quebec even for the mid-term future (2040-2069) and

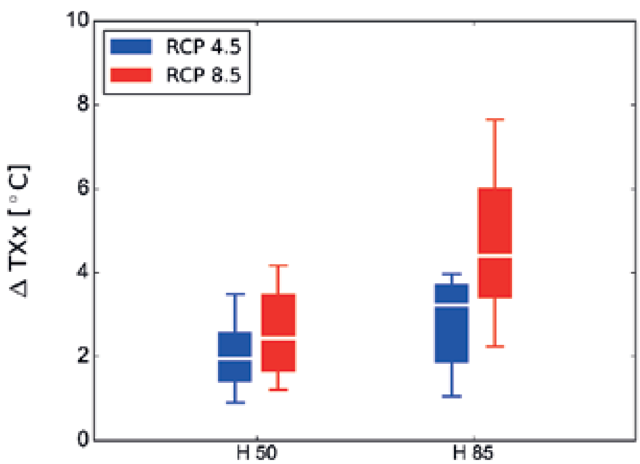


Figure 7. Box plots of mean regional projected changes over the IRIS-4 region of the annual maximum value of daily maximum temperature (TXx) indicator as projected by the RCP 4.5 ensemble simulations (in blue) and by the RCP 8.5 ensemble simulations (in red) for the two future periods (H 50 for 2040-2064 period and H 85 for 2076-2100 period).

RCP 4.5 scenario (smallest radiative forcing scenario). The largest increases are expected for the RCP 8.5 scenario at the end of the century. Agreement between simulations is wide spread (grid points without 'x') but the climatic signal for some regions (e.g., Quebec North Shore region) remains weak or unclear. Figures similar to Figure 6 were generated for all climate indicators.

Results were also summarized through the distribution of mean regional changes projected by the various simulations over the IRIS-4 domain. Figure 7 presents an example for the spatial mean of changes of the annual maximum value of daily maximum temperature (TXx) indicator as projected by the RCP 4.5 and RCP 8.5 ensemble simulations. This type of graph shows that expected mean changes over the whole domain will not be very different for the two RCPs for the 2040-2064 period (~ 2-3°C) but important differences may appear between these two forcing scenarios for the 2076-2100 period. These plots give a portrait of the overall projected changes for the IRIS-4 region (but provide no local information). Similar figures were generated for all climate indicators.

Tables gathering information about median values of mean regional projected changes, as well as lower and upper bounds of the projected changes were also presented. Table 8 presents an example of such table for temperature-related indicators. The table also contains regional mean values for the reference climate. Similar tables were generated for the other group of indicators.

Post-processing methods

Multivariate post-processing methods and their added value

The added value of multivariate quantile mapping (QM) relative to univariate QM has been investigated for 26 Canadian Arctic coastal sites with daily weather records for both temperature and precipitation. An ensemble of 13 simulations from global climate models (GCMs) has been post-processed. What was found basically is that temperature and precipitations time series are often positively correlated in winter (January) and often negatively correlated in summer (July). Generally, models do not adequately reproduce these correlations, and applying univariate QM does not improve this situation (correlations remain unchanged after applying univariate QM). Applying multivariate post-processing results in correlation coefficients closer to the observed values, while correcting other basic single-variable statistical properties (e.g., mean and standard deviation) just as the univariate method does.

Two other modifications to the QM technique were also tested. First, it was observed that (multivariate) QM can modify the simulated long-term trend, by as much as 1.5°C/decade (worst case); using a detrending-retrending procedure, alteration to the long-term trend could be almost eliminated. This improvement could be used in the generation of climate scenarios for an ArcticNet partner project (Gauthier et al. 2016). Secondly, it was shown that monthly transfer functions can lead to climatological discontinuities in the final scenarios at the month-to-month passages. This

Table 8. Median of projected changes in regional mean temperature-related indicators (Table 4) for the two future periods (H50 and H85) and two RCPs and spatial mean of the reference period. Lower and upper bounds of the simulated changes are presented in parenthesis. The reference climate is AgMERRA.

Indicator (unit)	Regional mean projected change				Regional mean of the reference climate (1980-2004)
	H50 (2040-2064)		H85 (2076-2100)		
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	
Annual mean T (°C)	3.7 (1.8:4.0)	3.9 (2.1:4.8)	4.7 (2.4:5.2)	6.7 (4.0:8.7)	-4.0
DJF mean T (°C)	5.9 (2.7:7.0)	5.9 (3.2:7.3)	7.0 (3.9:8.3)	10.5 (5.7:12.7)	-19.8
JJA mean T (°C)	2.3 (1.2:3.2)	2.5 (1.5:4.3)	2.8 (1.5:4.0)	5.2 (2.9:7.7)	10.2
ID (days)	-27 (-30:-16)	-28 (-35:-18)	-35 (-41:-20)	-51 (-68:-34)	164
Nthaw (days)	-1 (-1:1)	-1 (-2:1)	0 (-2:0)	-3 (-6:1)	16
TDD (degree days)	429 (211:512)	407 (243:713)	576 (255:682)	882 (452:1404)	1303
FDD (degree days)	-874 (-1008:-436)	-902 (-1164:-515)	-1069 (-1236:-606)	-1516 (-2004:-992)	2764
HDD (degree days)	-1308 (-1430:-642)	-1359 (-1678:-764)	-1641 (-1825:-854)	-2424 (-2904:-1436)	7678
GDD (degree days)	307 (123:379)	256 (140:537)	409 (159:499)	633 (282:1073)	635
SSD (calendar days)	-14 (-16:-6)	-11 (-19:-8)	-17 (-21:-8)	-25 (-37:-15)	148
SED (calendar days)	12 (9:15)	17 (11:21)	19 (10:22)	31 (21:40)	272
SSL (days)	26 (16:30)	28 (19:38)	36 (18:41)	55 (36:73)	124
TNn (°C)	7.4 (2.7:8.7)	6.4 (3.8:10.1)	9.4 (4.5:11.1)	14.5 (7.8:18.2)	-39.1
TN10 (°C)	6.9 (3.1:8.3)	6.5 (3.7:8.8)	8.8 (4.6:10.3)	13.1 (6.7 :15.6)	-28.3
TX10 (°C)	5.9 (2.8:7.9)	6.2 (3.3:8.0)	7.1 (4.0:9.4)	10.5 (5.7:13.5)	-17.8
TN10p (%)	-8.3 (-8.6:-6.2)	-8.5 (-9.3:-7.4)	-9.0 (-9.4:-7.8)	-9.8 (-9.9:-9.6)	9.9
TX10p (%)	-8.1 (-8.4:-5.8)	-8.3 (-9.0:-7.0)	-9.0 (-9.3:-7.4)	-9.8 (-9.9:-9.0)	9.9
TXx (°C)	1.9 (0.9:3.5)	2.4 (1.2:4.2)	3.2 (1.0:4.0)	4.4 (2.2:7.6)	25.2
TX90 (°C)	2.1 (1.0:3.1)	2.4 (1.5:4.1)	3.0 (1.4:3.7)	4.9 (2.7:7.4)	17.2
TX90p (%)	13.8 (7.4:18.5)	15.6 (9.4:23.2)	18.9 (9.7:24.2)	32.7 (20.0:48.5)	9.9
TN90p (%)	17.1 (8.9:20.0)	18.1 (10.9:26.6)	23.5 (12.5:27.4)	41.9 (28.0:56.0)	9.9

problem could be eliminated by using daily transfer functions. Detailed results have been published in Gennaretti et al. (2015).

One limitation with the tested (bivariate) approach is that transfer functions must be defined on a small number of data, making it numerically unstable. This could partially be compensated by increasing the width of the moving window, but this would not be sufficient when post-processing more variables (e.g., trivariate analysis). Hence, the advantages of working with a multivariate approach cannot always be used.

Inter-variable physical consistency in statistical post-processing

Climate scenarios generated by statistical post-processing techniques cannot be considered plausible if they show some form of physical inconsistency. This is often referred to in the literature (e.g., Ehret et al. 2012; Hewitson 2014; Vrac and Friederichs 2015), but rarely conceptualised beyond vague qualitative sentences. This issue was investigated by classifying physical inconsistency into two types. Type I refers to single-variable inconsistency (when a variable has a value out of its possible physical range) while type II refers to inter-variable inconsistency (when a defined mathematical relationship between several variables is changed). Generation of type II inconsistencies between daily temperature extrema (Tmin > Tmax) was investigated for the maritime Hudson Bay area (Agbazo and Grenier, to be submitted). Inconsistency of types I and II were investigated for twelve sites across North America by Grenier (2018), and two sites of the Canadian territories (Iqaluit and Yellowknife) were selected in order to verify that general findings can be applied in the North.

Main objectives and results from Agbazo and Grenier (to be submitted) are the following. Considering that univariate QM may generate a problem of physical inconsistency (PI) between Tmin and Tmax, leading to Tmin > Tmax situations, Thrasher et al. (2012) had previously introduced the general idea to post-process DTR (which stands for diurnal temperature range and is defined as DTR = Tmax - Tmin) and Tmax, and then to estimate Tmin (Option 1), or post-processed DTR and Tmin, and then estimate Tmax (Option 2). These authors recommended option 1 (tested on land grid-points). We investigated these options which were tested on a maritime domain (Hudson Bay area) and a third option was considered, namely post-processing of DTR and Tmean, and then estimate both Tmin and Tmax. The specific objectives of this analysis were: 1) to investigate the conditions under which PI situations are generated; 2) to study the impact of different numerical choices of the QM technique on the generation of PI; 3) to compare the three statistical post-processing approaches in terms of loss of statistical equivalence with the reference product.

Results showed that: the PI situations appear preferentially for small simulated DTR values, but the differential between the respective biases on Tmin and Tmax also plays an important role. Therefore PI situations cannot be corrected by simply adjusting parameters and options of QM. However preserving simulated trends generally leads to fewer PI situations. Globally, option 1 is the best strategy to avoid physical inconsistency because the loss in statistical equivalence of the deduced variable with its corresponding reference observational product is lower (it is unavoidable that a variable not directly post-processed but rather deduced from other post-processed variables will not perfectly match with its corresponding reference product, and this statistical mismatch was the criterion the select the best alternative among the three candidates).

Potential physical inconsistency in relative humidity (RH), specific humidity, temperature and pressure at 12 sites representing various climate regions across North America was investigated (Grenier 2018). Ten simulations (3-h time step) were used, and the CFSR reanalysis was used as reference dataset. For type I PI , results indicated that direct post-processing of RH generates a few number of supersaturation values (> 100%). However, generated supersaturation amplitudes may exceed observed values in fog and clouds. Supersaturation values are generally more frequent and higher when RH is deduced from post-processed parent variables rather than directly post-processed. Yellowknife was often the site with the highest frequency of occurrence of physical inconsistency, whereas Iqaluit was globally near the median. For type II PI, results showed that univariate QM practically always breaks the inter-variable thermodynamic relationship between the investigated variables. Heuristic proxies were designed for comparing the initial bias with the physical inconsistency of type II, and results suggested that QM generates a problem arguably lesser than the one it is intended to solve. When physical inconsistency was avoided by capping one humidity variable at its saturation level and deducing the other, statistical equivalence with the reference product remained much improved relative to the initial situation. The main recommendation for climate services was to post-process RH and deduce specific humidity rather than the opposite (also valid for Yellowknife and Iqaluit).

Post-processing methods application to less-investigated climate variables (e.g. wind, humidity)

The different tests for improving the post-processing techniques as well as the generation of scenarios for downstream impact studies has involved variables other than the well investigated temperature and precipitation. For example, modeling of wave and fast ice in Hudson Bay requires wind (along with temperature) scenarios. This involved making variable-specific technical choices, for example regarding post-processing the wind speed vector or the two individual horizontal components and regarding the nature of the transfer functions (multiplicative or additive). Also, analysis of the performance of the QM technique involved checking the impact on many statistical properties of the simulated time series, as illustrated in Figure 8. Figure 8a shows, for one simulation and one grid-point over the Hudson Bay domain, how the negative bias in the meridional wind component (variable "vas") during the cold months is adjusted to

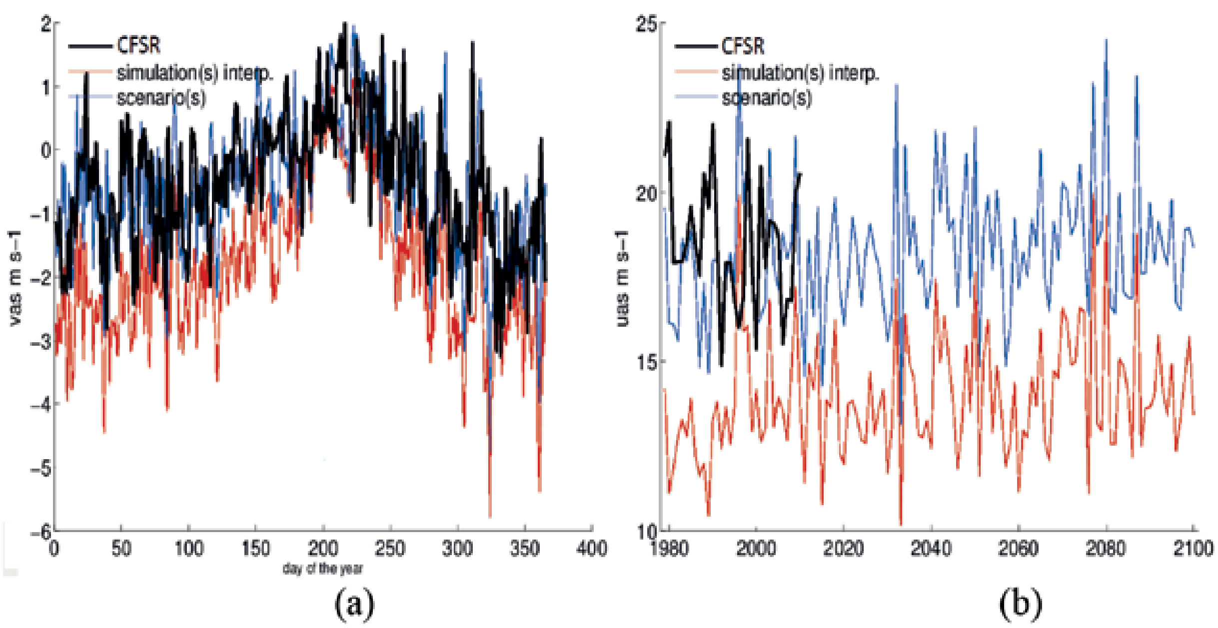


Figure 8. Examples of the application of the quantile mapping (QM) technique to wind components: (a) 32-yr average (1979-2010) (calibration period) for each day of the year and reference dataset (CFSR, in black), the simulation to be post-processed (red), and the resulting scenario (blue); (b) annual maxima of the 3-h time series over 1979-2100 (application period), with the same color code.

adopt values closer to the reference dataset (here the reanalysis CFSR), whereas Figure 8b shows how QM alters annual maxima of the zonal component (variable "uas"). Such analysis (conducted with six simulations and 2153 grid-point covering Hudson Bay and Hudson Strait) has revealed that QM is generally appropriate to generate plausible climate scenarios from climate simulations. This was partly expected *a priori*, except for extremes for which the basic QM technique is not designed. But results show that even without a special treatment for extremes, QM operates with a high degree of satisfaction. Of course, the relevance of the generated scenarios always depends on the quality of the selected reference dataset.

Other daily variables on which post-processing (quantile mapping) has been applied are relative humidity, specific humidity, and pressure, as mentioned in results of Objective 2.2. For the 51 annual indicators in the IRIS-4 report, the post-processing technique used was much simpler (adjustment of the mean), and involved indicators of snow cover.

Added-value of performance-based selection of simulations (prior to post-processing)

Prior to post-processing of climate simulations, scenario construction generally involves a selection step. Considerations in the selection of simulations (among all those available) generally include uncertainty coverage, computational capabilities of the user, and preference for, or importance of, higher spatial resolution in a given project. Another consideration was explored in this project, namely the performance of the models, within the "emergent constraints" framework (Bracegirdle and Stephenson 2013; Borodina et al. 2017). The idea here is to seek for relationships between, on the one hand, historical performance for some variables (called predictors) and, on the other hand, long-term climate change in some other (or the same) variables (called responses).

Preliminary work done by a master's student whose specific project started during the third year of the

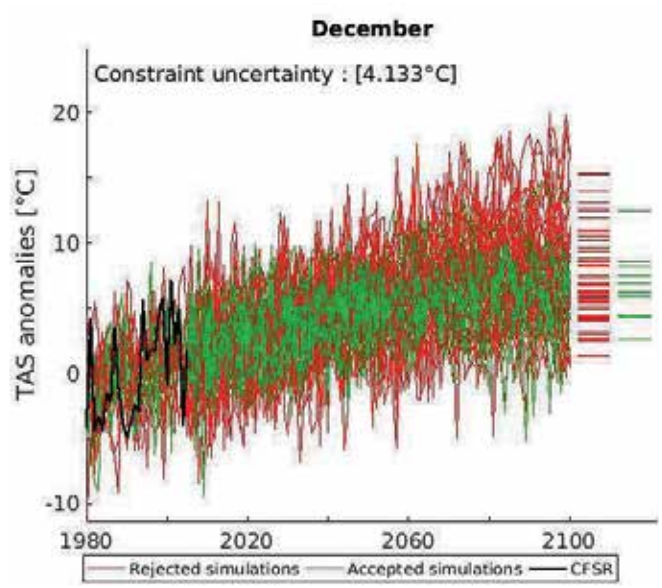


Figure 9. Monthly evolution of surface air temperature anomalies. The green (red) line represents an accepted (rejected) simulation based on the performance in the December average SIC during the reference period (1980-2005). The black line represents the reference dataset (reanalysis CFSR). Shown in the upper left corner, the "constraint uncertainty" represents the difference between the spreads of the initial (rejected plus accepted) and final (accepted) ensembles in terms of temperature (variable "tas") change (between 1980-2005 and 2075-2100). Horizontal green (red) lines displayed on the right hand side of the time series represent the 2075-2100 temperature anomalies for accepted (rejected) simulations.

whole project are presented. These preliminary results are however promising since strong relationships have been found between performance in reproducing the sea ice cover (predictor) and long-term climate change in temperature (response) over the Hudson Bay area (Giguère and Grenier, 2017). To be meaningful, emergent constraints must be statistically robust and physically justified, which is the case in those found in this specific objective. One very important advantage of finding strong emergent constraints is that these imply a reduction in uncertainty on the climate change (Collins et al. 2012), which is welcome in the Arctic context because uncertainty on future change is precisely very large.

Figure 9 illustrates this reduction of uncertainty with an ensemble of 55 CMIP5 simulations of surface air temperature (variable “tas”) averaged over Hudson Bay and Hudson Strait. The use of sea ice concentration (SIC) as a predictor leads to a reduction of 4.33°C in uncertainty on the temperature change, with mostly very large changes being rejected (details in the caption).

Defining reference climates by combining observational and reanalysis datasets

The following paragraphs present a summary of the main results for this part of the project. A scientific article is actually written that will be provided a complete description of the methodology and results. This manuscript will be submitted in the coming weeks [Pérez-Bello A., Mailhot A. (2018)]. Defining a reference climate for Canada through the combination of observational and reanalysis datasets. To be submitted to Atmosphere-Ocean.

Observational and reanalysis datasets

Five reanalysis were considered in this study: CFSR, ERA-Interim, JRA-55, and MERRA (see Table 3 for a description of these reanalysis). The interpolated gridded-precipitation dataset from Natural Resources Canada (NRCan) generated from stations records using a thin plate spline smoothing algorithms (ANUSPLIN) was also considered (McKenney et al. 2011). This dataset was used for comparison purposes and to estimate missing values in station records. Since each dataset covers a different period, the common period, 1980-2009, was considered in the following.

Daily precipitation records from the Adjusted and Homogenized Canadian Climate Data (AHCCD) developed by Environment and Climate Change Canada (ECCC; Mekis and Vincent, 2011) and from the stations operated by Ministère du Développement Durable, de l’Environnement et de la Lutte contre les Changements Climatiques (MDDELCC) from Quebec were also used. Only stations with at least 10 valid years during the 30-year period 1980-2009 were retained (a valid year is defined as a year with less than 20% missing daily values) for a total of 2,160 stations across Canada mainly concentrated in the southern parts of the country. Available records also contain many missing data (only 10.8% of the stations have records covering the complete 1980-2009 period).

Climate precipitation indicators

Ten climate precipitation indicators defined by the Expert Team on Climate Change Detection and Indices (ETCCDI; Klein Tank et al. 2009) as well as mean annual precipitation (PRmean) have been considered. These ten ETCCDI indicators are: annual mean of daily precipitation (PRmean); number of wet days (PR1mm); annual maximum 1-day precipitation amount (RX1day); annual maximum 5-day precipitation amount (RX5day); simple daily intensity index (SDII); annual number of days with precipitation ≥ 10 mm (R10mm); annual number of days with precipitation ≥ 20 mm (R20mm); annual maximum number of consecutive days with precipitation < 1 mm (CDD); annual maximum number of consecutive days with precipitation ≥ 1 mm (CWD); annual total precipitation from days with precipitation ≥ 1 mm (PRCPTOT).

Comparison of precipitation indicators from OI and EnOI datasets to observed values

The comparison proceeded in two steps. The first one consists of comparing the ten precipitation indicators at all stations across Canada used to post-process each reanalysis (OI method) and all reanalysis (EnOI method). It was showed that reanalysis performance depends on considered indicator, the poorest performance being observed for the CFSR CWD indicator and the best for the JRA55 PRmean, R10mm and PRCPTOT indicators. The reanalysis with the globally best performance is JRA55 while CFSR and MERRA displayed the poorest global performance. Among the considered indicators, PRmean and PRCPTOT have the best overall performances while the indicator displaying the poorest performance is CWD. Average correlation coefficients between observed and reanalysis annual time series for all indicators are globally larger than 0.5. After applying OI, most indicators display correlation values larger than 0.9, while combining the various reanalyses through EnOI still improved the overall performance as correlation coefficients in that case are larger than 0.95. The indicators displaying the best performances are CDD, RX1day, and CWD.

These results confirm that annual series of precipitation indicators generated through OI and EnOI methods outperformed the corresponding reanalysis datasets therefore providing a better representation of the reference climate than individual or some averaging process applied to reanalyses. Also it showed that the EnOI method outperformed OI applied to individual reanalysis.

The second step consists in applying a cross-validation approach to assess the performance of OI and EnOI at points that were not used to upgrade the reanalysis. The subnetwork cross-validation approach proposed by Panthou et al. (2012) was used. Validation networks are generated by eliminating stations at varying distances in order to control the average distance between sites of the calibration and validation networks. Two types of calibration/validation networks were defined. Far networks were designed to assess the performance of the developed datasets to estimate values at distant locations from the calibration points, while Near

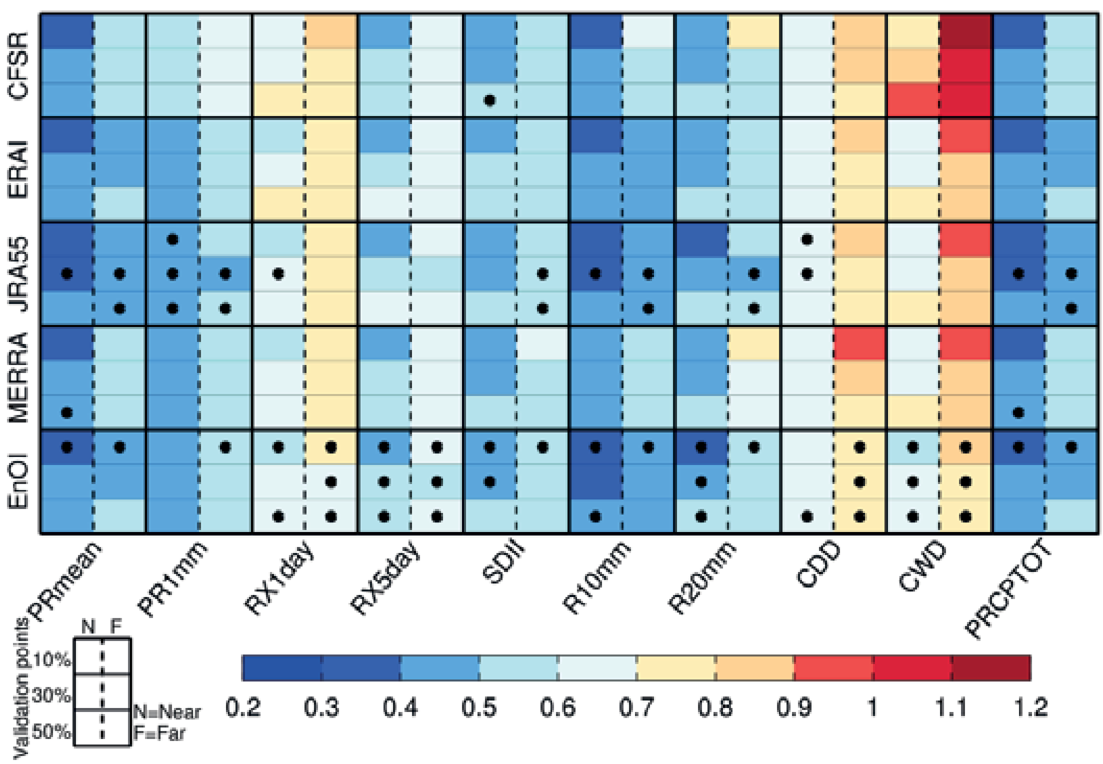


Figure 10. Normalized Root Mean Square Differences (NRMSD) over all validation sites for the period (1980-2009) (equation 1) for each indicator (x-axis). Near (N) and Far (F) configurations with 10, 30 and 50% of validation sites after applying OI to each reanalysis (top four rows) and after applying EnOI (bottom row). Black dots identify the datasets with the best performance (smallest NRMSD values) for a given subnetwork (N or F with 10, 30, or 50% validation points) and indicator.

networks were designed to assess the performance for locations close to the calibration points (Panthou et al. 2012). Different validation networks including 10, 30, and 50% of the stations from the initial network were defined for the Far and Near network configurations.

The relative performance of the post-processed OI and EnOI datasets were compared using the Normalized Root Mean Square Differences (NRMSD) metric defined by:

$$\text{NRMSD} = \frac{\text{RMSD}}{\sigma} \quad (1)$$

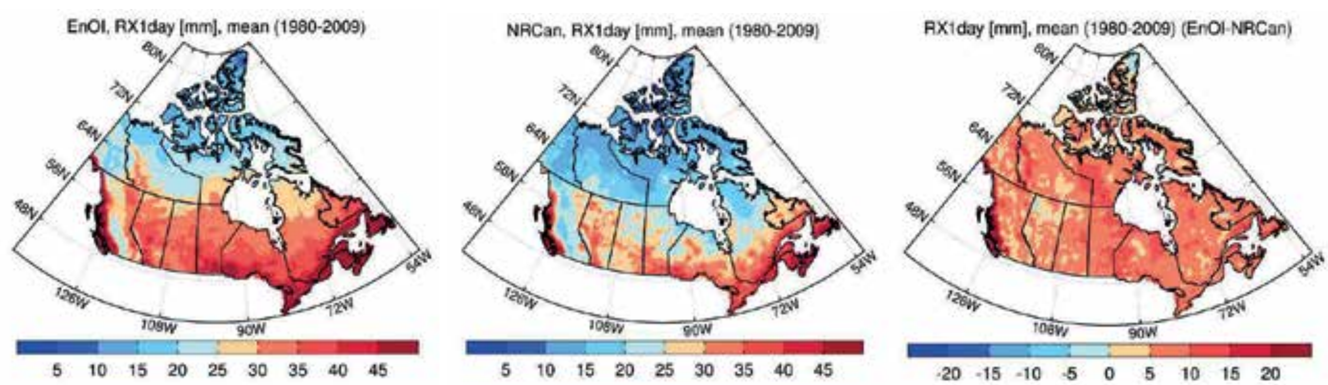
where RMSD is the Root Mean Square Difference between indicator annual series after applying OI or EnOI) and the corresponding values estimated from observed series, is the standard deviation for each indicator over all observed annual values at all validation sites. Therefore means of a perfect agreement between the considered dataset and the observed values, a value means that the average difference between annual post-processed and observed values is of the same order of magnitude as the spatial variability at validation sites.

Figure 10 summarized the results for all datasets, all cross-validation subnetworks and all indicators. It shows that, for most indicators and subnetworks, EnOI outperformed the OI datasets, followed by the dataset based on OI applied to JRA55, and finally by the dataset based on OI applied to MERRA and CFSR. It can be seen also that EnOI outperformed the other datasets for all indices for the Far configuration with 10% validation points corresponding to the case where the average distance between calibration and validation sites is the largest.

These results show that applying OI and EnOI methods led to an improved representation of the annual precipitation series across Canada compared to the initial datasets (single reanalysis) for all indicators and even at ungauged sites far from the sites that were used for OI and EnOI calibration (almost all NRMSD values are smaller than one). Also it shows that the EnOI in most cases outperformed OI. This last result is interesting as it shows that combining all the available information (all reanalyses) through EnOI is the best strategy.

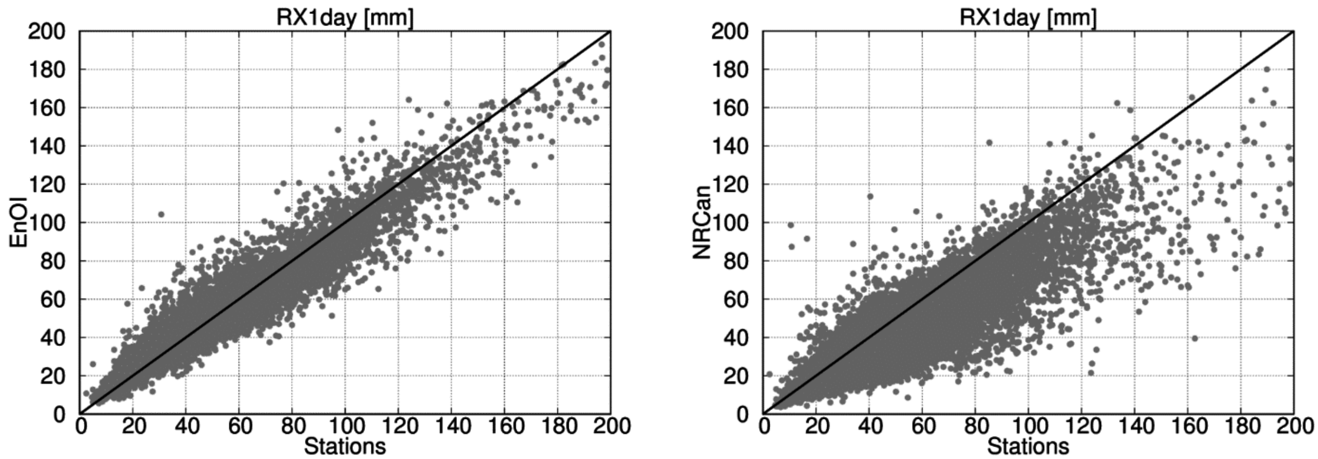
Comparison of EnOI and NRCan gridded interpolated datasets

The CPI dataset created from EnOI was then compared with the CPI values estimated from the NRCan dataset. Although NRCan is constructed by interpolation of station records and therefore should adequately be reproduced by indicator values at sites where stations are located, two major issues must be reminded regarding interpolated gridded dataset. First, station



(a) (b) (c)

Figure 11. Mean annual 1-day maximum precipitation (RX1day) over the 1980-2009 period as estimated from (a) EnOI; (b) NRCan; and (c) grid-to-grid differences between EnOI and NRCan values.



(a) (b)

Figure 12. Squatter plots of (a) EnOI (y-axis) and (b) NRCan mean annual 1-day maximum precipitation (RX1day) over the 1980-2009 period compared to the corresponding values estimated from observed series (x-axis).

density has an impact on the estimated precipitation suggesting possible large errors in gridded precipitation products for sites far from station network when station density is low (Gervais et al. 2014). Secondly, representativeness error defined by Tustison et al. (2001) as 'the errors in representing data (i.e. either model output or observations) at a scale other than their own inherent scale' may as well be influenced by the interpolating procedure. The NRCan dataset (0:083° x 0:083°) has a finer spatial resolution than EnOI (0:312° x 0:312°) and therefore it was necessary to remap NRCan dataset to the EnOI grid resolution in order to do a grid-to-grid comparison. A conservative remapping method (Jones, 1999) was used. It is important to note that some stations used in this study were not part of the station records used to develop the NRCan dataset (e.g. some stations operated by the MDDELCC).

Figure 11 shows an example of results for the mean annual 1-day maximum precipitation (RX1day) over the 1980-2009 period as estimated from EnOI and NRCan datasets with the corresponding grid-to-grid differences. As can be seen, NRCan estimates are almost systematically smaller than the EnOI estimates. Comparison of the other mean precipitation indicator values shows that the smallest differences between EnOI and NRCan datasets were observed for PRmean (in general smaller than 0.5 mm/day) with mostly smaller values for the NRCan dataset. PR1mm values for EnOI are globally lower than NRCan values (especially in the center and south part of the study area). In the north part, NRCan also presents a small area with lowest values for this index.

Comparing the EnOI and NRCan mean RX1day values to corresponding values estimated from station records shows that NRCan globally underestimated observed values (Figure 12). Similar graphs also show that NRCan presents light underestimation compared to observations for PRmean index while PR1mm values estimated from NRCan dataset overestimate the observation values.

Modeling of wave and fast ice dynamics in Baffin Bay and Hudson Bay

More than 89 figures were produced showing the reference climate and climate change between two future periods (2040-2064 and 2076-2100) and the

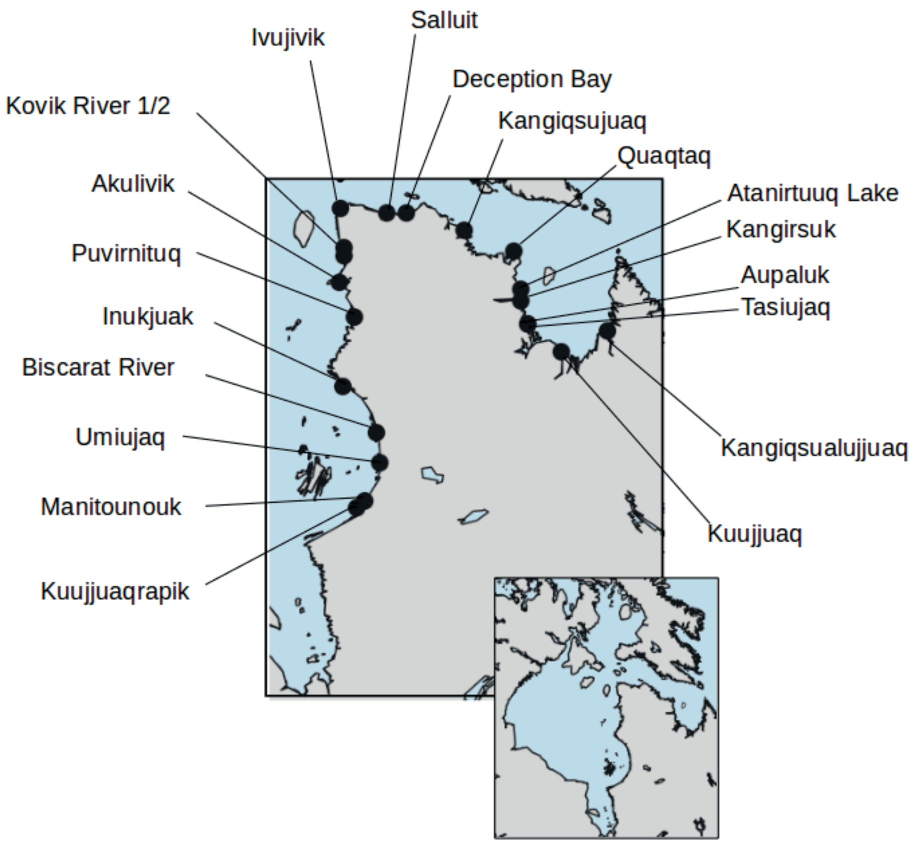


Figure 13. Geographical positions of the stations located along the Nunavik coasts.

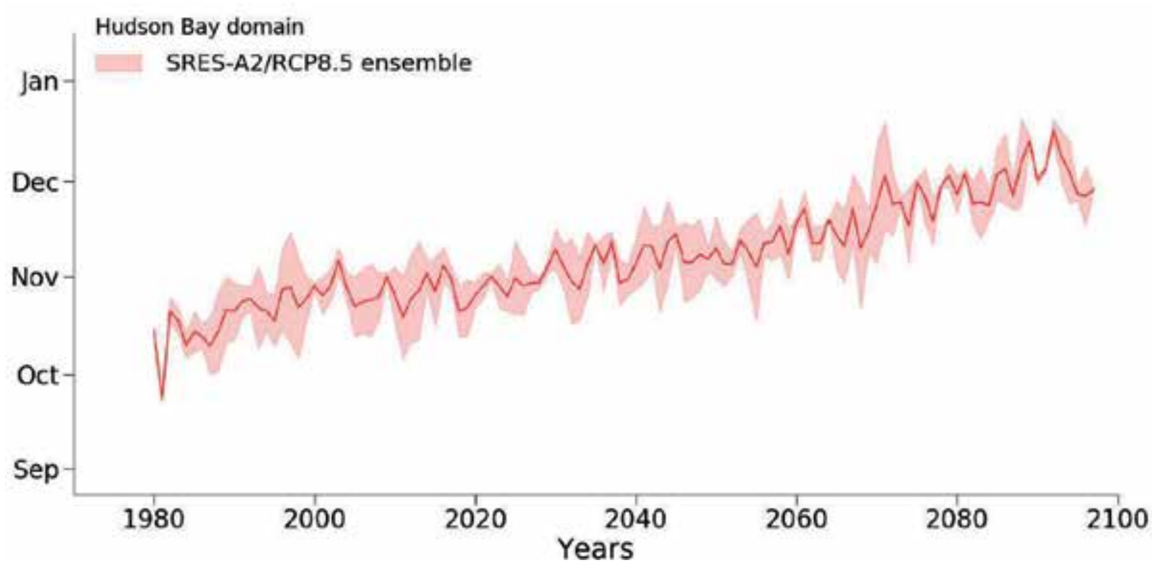


Figure 14. Time evolution of ice freeze-up date over the Hudson Bay domain. The red zone delineates the results for the ensemble of simulations while the red line corresponds to the mean simulated value.

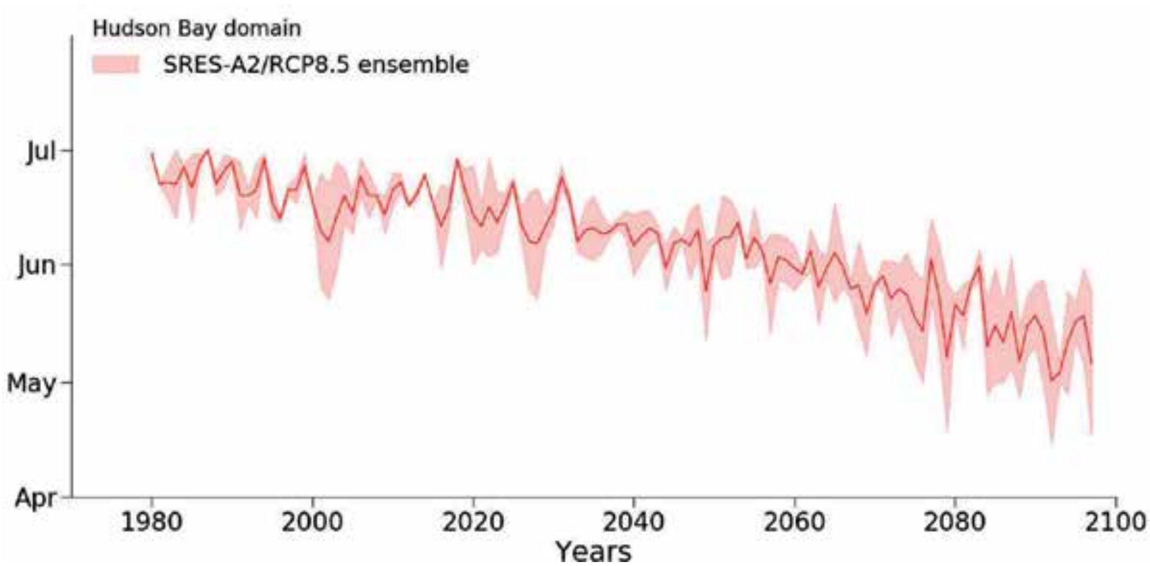


Figure 15. Time evolution of ice melt-onset date over the Hudson Bay domain. The red zone delineates the results for the ensemble of simulations while the red line corresponds to the mean simulated value.

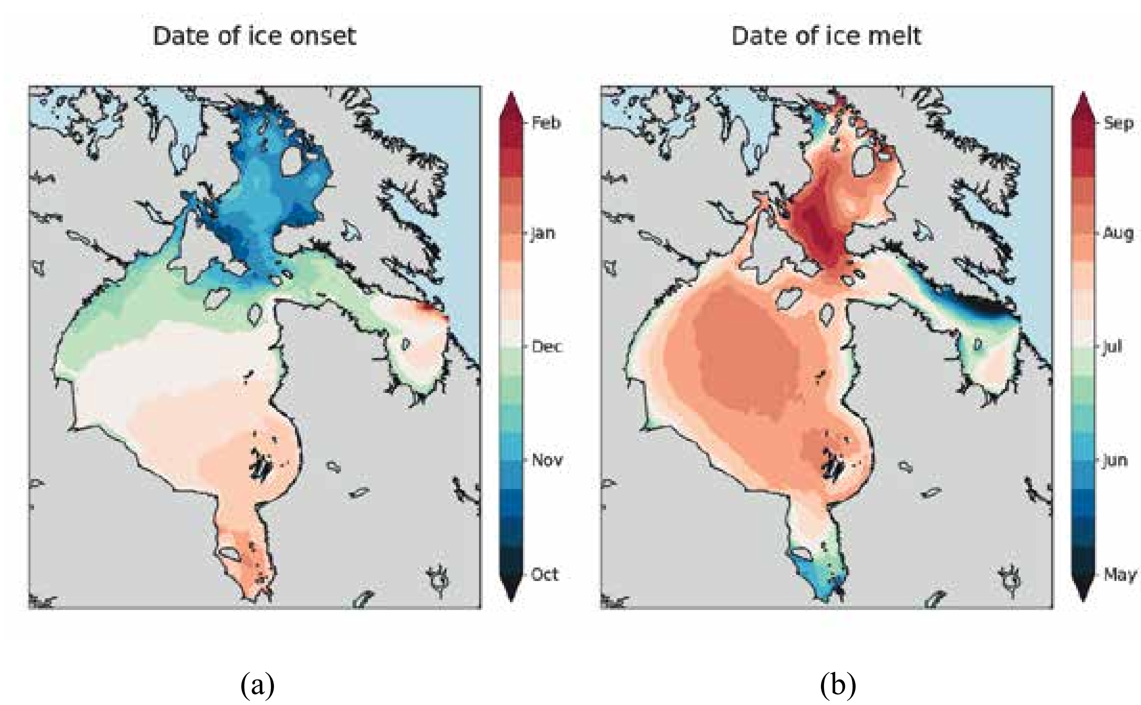
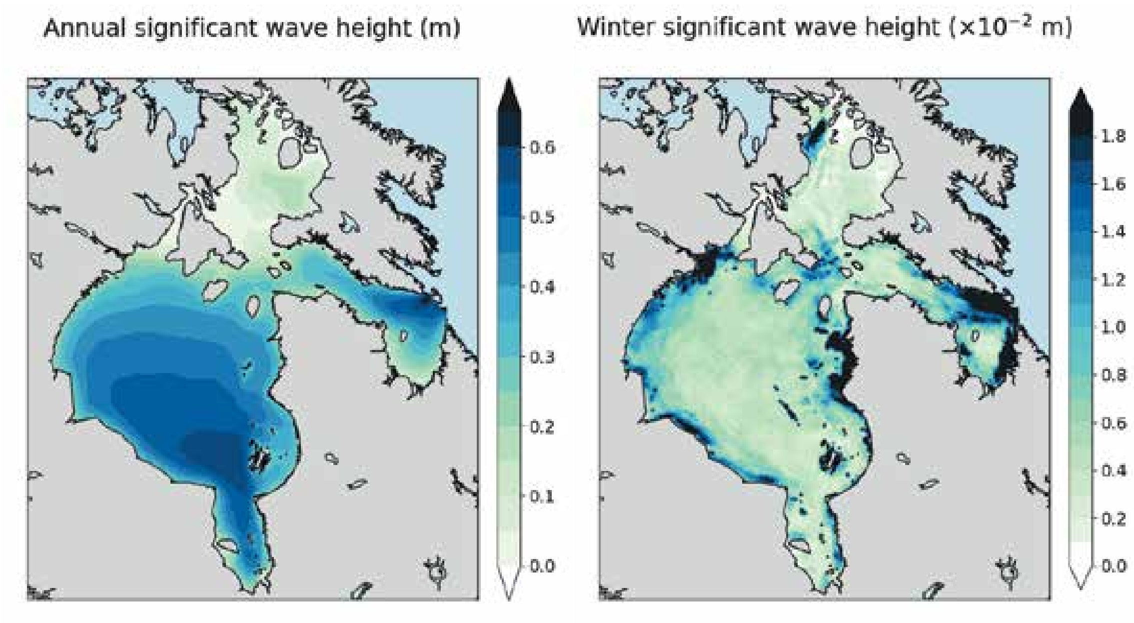


Figure 16. (a) Average date of ice freeze-up and (b) melt onset over the Hudson Bay domain for the reference climate period (1980-2004).



(a) (b)

Figure 17. (a) Annual and (b) winter significant wave height (m) over the Hudson Bay domain for the reference climate period (1980-2004).

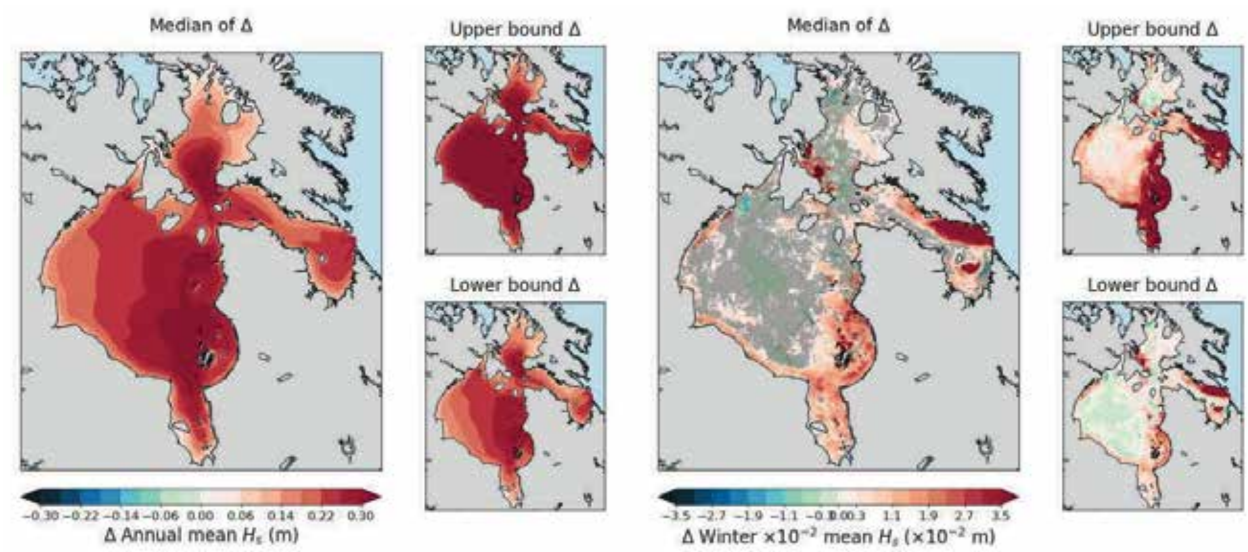
reference climate (1980-2004) for all coastal climate indicators listed in Table 1. Results are presented as 25-year averages over the Hudson Bay domain, as time series of domain averages or as time series at a given station. Twenty stations have been identified based on the presence of communities, key infrastructures or other ongoing research projects (Figure 13). Only a subset of these figures are presented and described here. The complete list will be made available as part of the IRIS-4 report and associated material.

Sea ice climate

Figures 14 and 15 show the projected changes in ice conditions over the Hudson Bay as estimated on the basis of simulations aev-bTp and ahj (both using the IPCC SRES-A2 greenhouse gas emission scenario). These results mirror those obtained by Senneville and St.Onge-Drouin (2013) and show a somewhat linear decrease trend of the ice-covered season of about -80 days per century. These results can be compared to the mean annual date of ice freeze-up and melt onset over the Hudson Bay for the reference climate (Figure 16).

Wave climate

Figure 17 shows the annual and winter mean significant wave height over the Hudson Bay domain. Note that larger waves during winter, even though they are only a few centimeters high, occurs near the coasts while during summer they happen offshore. This means that during winter, strong wind events are associated with the opening of coastal polynyas in which waves are generated. The annual and winter mean significant wave height are shown in Figure 17. The winter mean value is computed over the winter, whose ending dates are determined by the dates of sea-ice freeze-up and sea-ice melt, which change from one period to another. The overall increase in annual significant wave height results from the fact that the wave season is longer and that higher waves are generated during the late fall and early seasons.



(a) (b)

Figure 18. (a) Annual and (b) winter climate-mean differences between the future period (2076-2100) and the reference period (1980-2004) for the mean significant wave height. The large map of each panel (a and b) shows the median of the simulated differences at each grid-point. Grid-points where models do not all agree on the sign of change (positive or negative) are indicated with an x. The small secondary maps give an indication of the dispersion of the projected changes by the ensemble. The 'Upper bound Δ' map shows the simulation with the largest mean projected differences over the domain, while the 'Lower bound Δ' map corresponds to the simulation with the smallest projected changes.

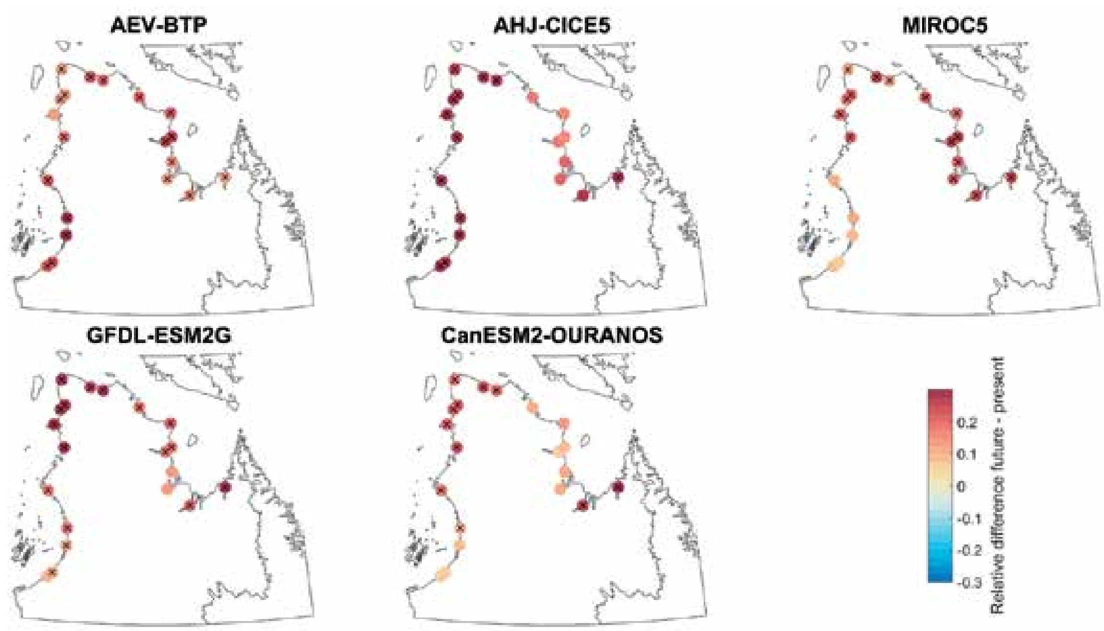


Figure 19. Differences in annual maximum wave height quantiles (2065-2099 period versus reference period 1980-2004), for the annual maximum 1-h wave height with 2-year return period estimated from the various simulations. Crosses indicate that the differences between future and reference climate are statistically significant (Mann-Kendall test at 95% confidence level).

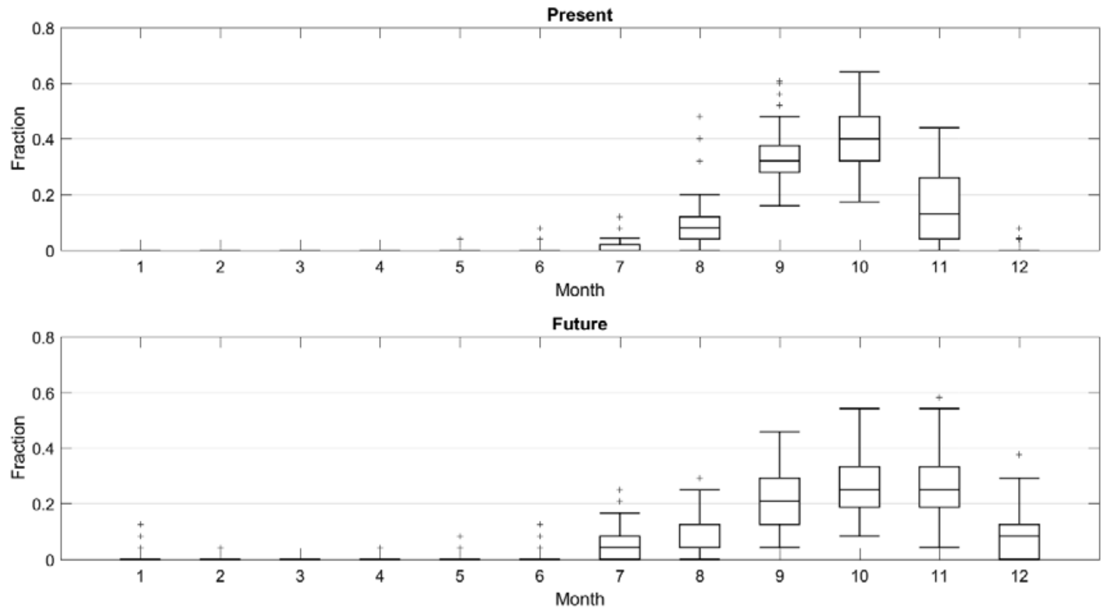


Figure 20. Box plots of the fraction of time annual maximum 1-h annual maximum wave height occur in each month during the reference period (1984-2009; top panel) and in future climate (2070-2100; bottom panel).

Frequency analysis of extreme wave height were also carried out. Annual maxima series at the 20 coastal sites (Figure 18) were extracted from hourly wave height series for different durations (1, 2, 6, 12 and 24 hours). Extreme quantiles were then estimated using the Gumbel distribution. Results obtained using the Generalized Extreme Value (GEV) distribution were very similar. Four return periods were considered: 2, 5, 10 and 25 years. The extreme quantiles were assessed for the reference and the two future periods. Differences between future and reference wave height quantiles were estimated at each coastal site, for each duration and each return period. Significant trends in annual maximum wave height series over the 1980-2099 period were assessed using the Mann-Kendall test (95% significance level).

Results show a general increase in the annual extreme wave height in the future. For example, Figure 19 presents the difference for the 1-hour, 2-year return period annual maximum wave height between the end of century and the reference periods. Depending on the simulation, 55% to 95% of the sites displayed a statistically significant increase in extreme wave height while the median increases range between 10 to 30%. However, Figure 5 shows the weak consistency of projected changes since coastal sites with significant changes differ from one simulation to the other. Finally, it should be noted that the conclusions are similar for all durations or return periods.

Finally the change of the date of occurrence of maximum wave height was investigated (Figure 20). For the reference period, annual maximum usually occurs between August and November (top panel) while for the 2076-2100 period, the annual maxima more frequently occur in July and December (lower panel). This suggests that the ice-cover duration will get shorter in the future, thus allowing for a longer period where the coast will be vulnerable to high wave events.

Wave-ice climate

Wave-ice interaction processes simulated by the model are, on the one hand, the attenuation of wave energy by sea ice and, on the other hand, the wave-induced break-up of the ice. Note that the ice-ocean and the

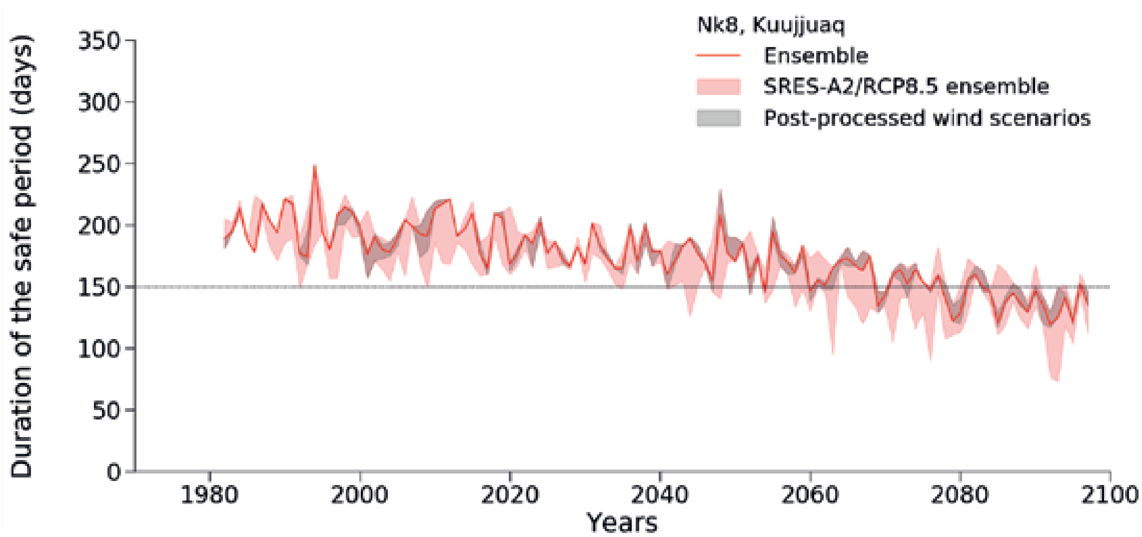


Figure 21. Annual time series of the duration of the safe period for the near-station indicator value at Kuujjuaq (Figure 1). The shaded zones delineate the results from the ensemble of simulations (red, SRES-A2 ensemble, and gray, SRES-A2/RCP8.5 ensemble, which includes the post-processed wind scenarios).

wave model are not coupled at runtime but one is rather forced by the other, i.e. the wave model reads ice concentration and thickness, reinitialize floe size, propagate wave and break sea ice. When sea ice is broken up by waves, it is assumed that the ice cover is not safe neither for travel nor for protection. This allows us to determine a period during which ice is not broken-up by waves, i.e. a safe period indicator (see Table 1). Figure 21 shows an example of time series of the duration of the safe period near Kuujjuaq (Figure 1).

Another relevant indicator for the protective role of sea ice is obtained by computing the minimum sea ice thickness that can resist to the destructive power of the simulated waves at a given point. One can compare this value to the simulated mean thickness and evaluate the stability of the given ice cover. However, the 10-km resolution coupled ice-ocean model does not resolve ice forming nearshore that could effectively protect the coast. The minimum (or critical) ice thickness is thus a useful value informing on the wave energy impacting a particular location and the physics of wave-induced ice fracture.

DISCUSSION

Climate indicators in historical and future climate

This study has provided climate change projections based on a large multi-model ensemble of CORDEX RCMs. Compared to previous studies of climate change over Canada (e.g., Allard and Lemay 2012; Stern and Gaden 2015), this ensemble provides new insight into model uncertainty assessment. Also, the comparison of annual mean temperature and precipitations over Canada, obtained from the new CORDEX ensemble with the one from a 39-member CMIP5 ensemble showed that RCM large-scale projected changes were consistent with that projected by the CMIP5 ensemble. However, precipitation changes in the RCM ensemble were larger over some regions with important topography (e.g., Torngat Mountains in Northern Quebec). This may be due to the more accurate representation of orographic precipitation by RCMs, which gives an important added-value to these climate projections.

In the Canadian Arctic context, the identification of the reference dataset is a major challenge because of the poor coverage by meteorological networks. The newly proposed datasets enabled a more comprehensive analysis of the reference climate and enabled the creation of high-resolution gridded maps. Uncertainty on reference climate values, defined through the biases between the reference climate values and the corresponding station values, was also provided, which was not the case of previous studies (e.g. Allard and Lemay 2012; Stern and Gaden 2015). The number of climate indicators was also larger with new indicators related to total precipitation, solid precipitation and temperature extremes.

The analysis of projected changes over the IRIS-4 region showed important changes for a large variety of climate indicators. Continuous annual time series of indicators over the IRIS-4 region, for the 1950-2100 period, were generated with the corresponding envelope of simulation results for the two emission scenarios. The two emission scenarios project similar changes for the next 50 years and start to diverge after 2060 for a large number of indices. The most important differences are projected for the end of century for the RCP 8.5 scenario. These differences are especially important for climate indicators related to winter (e.g., annual fraction of solid precipitation, freezing degree days, heating degree days, snow cover duration, December-January-February mean temperature) and to extremes (e.g., 99th percentile of daily precipitation, extremely wet days, precipitation on extremely wet days, frequency of warm nights, extreme cold nights).

The actual study adds information on the range of projected changes at each grid point by presenting not only the median change but also the upper and lower bonds of projections. Agreement between projected changes among the various simulations was also presented. All regional models agree for an important increase for many temperature indicators (e.g., thawing degree days, growing degree days, summer season length, mean seasonal, annual, maximum and minimum temperatures). The most important changes are projected for the end of the century by the RCP 8.5 scenario. The median value of mean regional change (over IRIS-4) for RCP 8.5, for the end of the century period, is 6.7°C for annual mean temperature, 10.5°C for winter temperature and 5.2°C for summer temperature. The ensemble of models also project increases in annual mean and in extreme precipitation, with extremes increasing more than annual mean precipitation. For the end of the century period, for RCP 8.5, the median value of mean regional change (over IRIS-4) of annual mean total precipitation is 0.7 mm/day, while the average regional value in historical climate is 2 mm/day. Corresponding values for precipitation due to extremely wet days (R99pTOT) are 78 mm for the projected change and 43 mm for the reference period.

Important decreases are projected for some indicators related to the winter period (e.g., number of freezing days, freezing degree days, heating degree days, frequency of cold nights or days, snow cover duration and maximum snow depth). For example, the number of freezing days will decrease by -51 days by the end of the century (RCP 8.5) in average over IRIS-4 region while the average regional value in reference climate (1980-2004) is 164 days. The median of the regional mean change in snow cover duration, for the end of the century, for RCP 8.5 over IRIS-4, is -60 days, while the corresponding value for the reference period is 216 days. Snow cover will in average start later during the year (the median of the IRIS-4 mean changes is 31 days) and disappear at an earlier date (the median of the IRIS-4 mean changes is 29 days). However, the overall change for liquid and solid precipitation indicators and for winter thaw events is small and simulations disagree on the sign of the change over large regions.

Post-processing methods

Statistical post-processing (SPP) of climate simulations (direct outputs from numerical climate models) is often a necessary step in the construction of climate scenarios (plausible climate trajectories) because climate simulations may present important biases and may not represent the same spatial scale as that wanted for a given project. An SPP technique is always a set of subjective choices to adjust statistical properties (e.g., mean, standard deviation, long-term trend, autocorrelation, inter-variable correlation, etc.) of a simulation to those of a reference product (in-situ observations, gridded dataset, reanalysis, etc.), with different choices implying different levels of sophistication. Unfortunately, any technique has the potential to generate problems, for example by inadvertently altering some statistical properties or by generating physical inconsistency. Hence, investigating the impacts of SPP methods like quantile mapping (QM) on climate simulations aims at verifying whether it can lead to such problems and how solutions can be found.

In this project, the QM technique has been improved by focusing on statistical properties like inter-variable correlations as well as the long-term trend, and by investigating strategies to avoid clear types of single-variable and inter-variable physical inconsistencies. The ultimate objective was to converge towards a technique that generates climate scenarios that are as plausible as possible. Overall, this objective has been reached very satisfactorily. However, it must be stressed that, although statistical post-processing consists of better known and still improving procedures, for many climate scientists a non-satisfactory aspect will always remain due to its very nature (non-physically-based). Hopefully, knowledge about physical processes of the climate system as well as computational power will continue to increase and will reach a point where statistical post-processing is no longer necessary.

Development of scenarios combining reference datasets

It is important to have an adequate reference climate when assessing the impact of climate change and comparing various adaptation strategies. However it can be challenging in remote regions historically poorly covered by station network. Reanalyses represent interesting alternative datasets for such regions. Ground precipitation records being not assimilated, precipitation simulated by reanalysis may however present large biases. Combining reanalysis and station records could therefore provide an improvement in the spatial representation of precipitation.

In this study, on-line modes of data assimilation techniques were applied using OI and EnOI methods. These methods combine different datasets where the resulting field is expected to provide a better representation of the historical climate. The OI method was applied by combining each reanalysis independently with the available station records while the EnOI method combines station records with the information provided by all the reanalyses (as an ensemble). A period of 30 years (1980-2009) was used. Ten climate precipitation indicators were estimated for each dataset.

In order to verify the performance of the dataset created after applying each assimilation method, a statistical analysis was first performed comparing the post-processed annual precipitation indicator values over the 1980-2009 period at each observational site to the corresponding grid-point values estimated through OI or EnOI. Results showed that reanalysis performance strongly depends on considered indicators. For instance, indicators displaying the best overall performance were annual mean precipitation (PRmean) and the annual total precipitation from days with precipitation ≥ 1 mm (PRCPTOT), while the indicator showing the poorest performance was the annual maximum number of consecutive days with precipitation ≥ 1 mm (CWD). JRA55 reanalysis globally outperformed the other reanalyses while CFSR and MERRA were the ones with the poorest global performance. As expected, OI and EnOI led to large reduction of the differences between observed and post-processed values at station sites.

Cross-validation was then applied in order to evaluate the performance at validation sites not included into the calibration process. Two different subnetworks

(Near and Far) were defined by taking into consideration the inter-distance between calibration and validation sites. Validation networks including 10, 30, and 50% of the stations from the initial network were defined. A total of 60 subnetworks per dataset (six per each indicator, three Near and three Far subnetworks) were used showing improvements in the estimated annual indicator values compared to their corresponding pre-processed values. These improvements were more important for indicators estimated from CFSR and MERRA reanalysis than for the other reanalysis. EnOI showed the best performance compared to OI applied to each reanalysis independently. Among the datasets resulting from applying OI, JRA55 and ERAI presented the best overall performance.

The CPI values produced by the EnOI method was finally compared with the corresponding values estimated from the NRCan dataset. A grid-to-grid comparison was carried out for three specific indices: annual mean daily precipitation (PRmean); number of wet days (PR1mm); annual maximum 1-day precipitation (RX1day). Differences between each of these datasets and observed values remained small for PRmean while NRCan globally overestimated PR1mm values and underestimated RX1day values. Smoothing effects due to the interpolation method may partly explain these biases. These results show that NRCan should be used with caution for extreme indicators such as RX1day.

CONCLUSION

Climate indicators in historical and future climate

This study used a large number of climate simulations based on the new generation of RCMs. Climate change projections are presented on a high resolution grid of 0.25° for two emission scenarios, a medium-low emissions scenario (RCP 4.5) and a high emissions scenario (RCP 8.5), covering a large range of socio-political future evolutions. Therefore, this study offers a better understanding and representation of uncertainties both in terms of modelling uncertainties (multi-model ensemble) and future evolutions of greenhouse gases emissions (forcing scenarios). Also, the finer spatial resolution improves the representation of fine scale processes (e.g. orographic precipitation). These results will help stakeholders in decision making regarding the development of optimal adaptation strategies and the future development of the region.

The proposed 47 climate indicators (21 temperature, 12 total precipitation, 9 liquid and solid precipitation, and 5 snow depth indicators), selected after consulting stakeholders, offer a complete picture of the present and future climate over the Northern Canada. A comprehensive methodology for evaluating and selecting the reference climate from a large number of reanalysis, observed and model-generated datasets was developed. AgMERRA, a dataset that combines MERRA reanalysis with observational datasets from in situ observational networks and satellites, was selected to represent the reference climate for all temperature and precipitation indicators, while MERRA and MERRA2 reanalyses were selected for the liquid and solid precipitation, and the snow depth indicators respectively. Maps were created for each climate indicator based on the selected reference dataset. Each map is accompanied by a graph (violin plots) showing the distributions of biases between indicator values estimated from the selected reference dataset and those from station sites, providing a global picture of the possible bias of the reference dataset. Therefore, the selected climate indicators and the high-resolution gridded datasets used to represent the reference climate offer a complete and relevant picture of the actual climate of the Canadian Arctic.

Climate projections showing the time evolution (from 1950 to 2100) of the 47 indicators simulated by the RCP 4.5 and RCP 8.5 RCM simulation ensemble were also developed. Results were presented and summarized in various ways. Maps showing the spatial distribution of local (grid-point) projected changes over the IRIS-4 region for the RCP 4.5 and RCP 8.5 and for each future period (2040-2064 and 2076-2100) were created. Median values (mean of the distribution of changes as estimated for the available simulations at each grid-point), as well as for the most 'extreme' simulations (the one with the maximum and the minimal projected mean regional changes) were also created. Mean regional changes over the Nunavik-Nunatsiavut domain were reported in box plots where the mean regional changes for each climate indicator are displayed as well as the interquartile range of mean regional projected changes for both future periods and RCP, estimated from each ensemble simulation. Finally tables were also produced that summarized the mean regional projected changes for each climate indicator. These tables also contain the minimum and maximal regional projected changes. All these figures, maps, and tables are integrated into the PAVICS platform developed by Ouranos and partners.

These results will help identify the climate indicators that will be most affected by climate change, therefore providing local communities with crucial information in their assessment, evaluation and implementation of adaptation strategies.

Post-processing methods

This project has led to many improvements in the post-processing procedures used at Ouranos, a consortium providing climate services and scenarios mainly for studies in the province of Quebec including Nunavik, as well as for studies in other regions of Canada including Nunatsiavut, the three federal territories, and large northern water basins (e.g., Baffin Bay, Hudson Strait, Hudson Bay). These improvements included many conceptual novelties, for example regarding strategies to avoid inter-variable physical inconsistency, and regarding the improvements in the plausibility of the scenarios (e.g., preventing month-to-month discontinuities when monthly transfer functions are used in the quantile mapping technique). This project was also the occasion to refine our checkup scripts for generated scenarios, for example by analysing adjustment of diurnal cycles for wind and temperature scenarios used in downstream impact models for sea wave and sea ice (requiring 3-hour inputs). Finally, investigating Arctic regions was also the occasion to use the emergent constraints framework, with the presence of the sea ice cover allowing for predictor/response relationships that lead to reductions in uncertainty during some months of the year.

Development of scenarios combining reference datasets

The dataset produced in this paper provides a unique reference climate for the 1980-2009 period for many precipitation indices. This is especially valuable for northern regions poorly covered by station networks. Future work will look at the development of a similar method for daily precipitation series that could be used, for instance, for hydrological applications.

As many new datasets are developed combining different sources of information (satellites, reanalysis, meteorological model), the proposed methodology can be applied to readily improve our representation of the reference climate.

Modeling of wave and fast ice dynamics in Baffin Bay and Hudson Bay

The coastal marine climate will very likely significantly change over the next century. The ice-covered season will shorten significantly, beyond the simulated interannual variability, allowing stronger late fall and early spring winds to generate larger waves that will impact the coast.

REFERENCES

Alexeev, V.A., Esau, I., Polyakov, I.V., Byam, S.J., Sorokina, S. (2011). Vertical structure of recent arctic warming from observed data and reanalysis products. Climatic Change, 111:215-239, doi:10.1007/s10584-011-0192-8.

Allard, M., Lemay, M. (2012). Nunavik and Nunatsiavut: From science to policy. An Integrated Regional Impact Study (IRIS) of climate change and modernization, ArcticNet Inc., Quebec City, Canada, 303pp., available online at www.arcticnet.ulaval.ca/pdf/media/iris_report_complete.pdf. (accessed February 2018).

Bertino, L., Evensen, G., Wackernagel, H. (2007). Sequential Data Assimilation Techniques in Oceanography. International Statistical Review, 71:223-241, doi:10.1111/j.1751-5823.2003.tb00194.x.

Borodina, A., Fischer, E.M., Knutti, R. (2017). Emergent Constraints in Climate Projections: A Case Study of Changes in High-Latitude Temperature Variability. J. Climate, 30:3655-3670, doi:10.1175/JCLI-D-16-0662.1.

Bosilovich, M.G., Chen, J., Robertson, F.R., Adler, R.F. (2008). Evaluation of Global Precipitation in Reanalyses. J. Appl. Meteor. Climatol., 47:2279-2299, doi:10.1175/2008JAMC1921.1.

Bracegirdle, T.J., Stephenson, D.B. (2013). On the Robustness of Emergent Constraints Used in Multimodel Climate Change Projections of Arctic Warming. J. Climate, 26:669-678, doi:10.1175/JCLI-D-12-00537.1.

Brown, R.D., Brasnett, B. (2010). Canadian Meteorological Centre (CMC) Daily Snow Depth Analysis Data, Version 1 (updated annually), Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center, doi:10.5067/W9FOYWH0EQZ3.

Candiani, G., Carnevale, C., Finzi, G., Pisoni, E., Volta, M. (2013). A comparison of reanalysis techniques: Applying optimal interpolation and Ensemble Kalman Filtering to improve air quality monitoring at mesoscale. Sci. Total. Environ., 458:7-14, doi:10.1016/j.scitotenv.2013.03.089.

Collins, M., Chandler, R.E., Cox, P.M., Huthnance, J.M., Rougier, J., Stephenson, D.B. (2012). Quantifying future climate change. Nat. Climate Change, 2:403-409, doi:10.1038/nclimate1414.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Holm, E.V., Isaksen, L., Kallberg, P., Kohler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., Vitart, F. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quart. J. Roy. Meteorol. Soc., 137:553–597, doi: 10.1002/qj.828.

Diaconescu, E.P., Mailhot, A., Brown, R., Chaumont, D. (2018). Evaluation of CORDEX-Arctic daily precipitation and temperature based climate indices over Canadian Arctic land areas. Clim. Dyn., doi:10.1007/s00382-017-3736-4.

Diallo, I., Sylla, M.B., Giorgi, F., Gaye, A.T., Camara, M. (2012). Multimodel GCM-RCM ensemble-based projections of temperature and precipitation over West Africa for the early 21st century. Int. J. Geophys., 2012:1–19, doi:10.1155/2012/972896.

Donat, M.G., Sillmann, J., Wild, S., Alexander, L.V., Lippmann, T., Zwiers, F.W. (2014). Consistency of Temperature and Precipitation Extremes across Various Global Gridded In Situ and Reanalysis Datasets. J. Climate, 27:5019-5035, doi:10.1175/JCLI-D-13-00405.1.

Dosio, A., Panitz, H.J., Schubert-Frisius, M., Lüthi, D. (2015). Dynamical downscaling of CMIP5 global circulation models over CORDEX-Africa with COSMO-CLM: evaluation over the present climate and analysis of the added value. Clim. Dyn., 44(9–10):2637–2661, doi:10.1007/s00382-014-2262-x.

Dumont, D., Kohout, A.L., Bertino, L. (2011). A wave-based model for the marginal ice zone including a floe breaking parameterization. J. Geophys. Res., 116, C04001, doi:10.1029/2010JC006682.

Ehret, U., Zehe, E., Wulfmeyer, V., Warrach-Sagi, K., Liebert, J. (2012). HESS Opinions "Should we apply bias correction to global and regional climate model data?". Hydrol. Earth Syst. Sci., 16:3391-3404, doi:10.5194/hess-16-3391.

Fotso-Nguemo, T.C., Vondou, D.A., Pokam, W.M., Djomou, Z.Y., Diallo, I., Haensler, A., Tchotchou, L.A.D., Kamsu-Tamo, P.H., Gaye, A.T., Tchawoua, C. (2017). On the added value of the regional climate model REMO in the assessment of climate change signal over Central Africa. Clim. Dyn., 49(11-12):3813-3838, doi:10.1007/s00382-017-3547-7.

Gauthier, G., Péron, G., Lebreton, J.-D., Grenier, P., van Oudenhove, L. (2016). Partitioning prediction uncertainty in climate-dependent population models. Proc. R. Soc., B 283:2016-2353, doi:10.1098/rspb.2016.2353.

Gennaretti, F., Sangelantoni, L., Grenier, P. (2015). Toward daily climate scenarios for Canadian Arctic coastal zones with more realistic temperature-precipitation interdependence. J. Geophys. Res. Atmos., 120, doi:10.1002/2015JD023890.

Gervais, M., Tremblay, L.B., Gyakum, J.R., Atallah, E. (2014). Representing Extremes in a Daily Gridded Precipitation Analysis over the United States: Impacts of Station Density, Resolution, and Gridding Methods. J. Climate, 27:5201-5218, doi:10.1175/JCLI-D-13-00319.1

Giguère, V., Grenier, P. (2017). Emergent constraints framework: an application with sea ice concentration and surface air temperature over the Hudson Bay area. Poster presented at the 7th Ouranos Symposium, November, 15-17, 2017, Montreal.

Giorgi, F., Jones, C., Asrar, G. (2009). Addressing climate information needs at the regional level: the CORDEX framework. WMO Bulletin, 58:175-183.

Giorgi, F., Coppola, E., Raffaele, F., Diro, G.T., Fuentes-Franco, R., Giuliani, G., Mamgain, A., Llopart, M.P., Mariotti, L., Torma, C. (2014). Changes in extremes and hydroclimatic regimes in the CREMA ensemble projections. Climate Change, 125(1):39–51, doi:10.1007/s10584-014-1117-0.

Gutowski, Jr. W.J., Giorgi, F., Timbal, B., Frigon, A., Jacob, D., Kang, H.-S., Raghavan, K., Lee, B., Lennard, C., Nikulin, G., O'Rourke, E., Rixen, M., Solman, S., Stephenson, T., Tangang, F. (2016). WCRP COordinated Regional Downscaling EXperiment (CORDEX): A diagnostic MIP for CMIP6. Geosci. Model Dev., 9:4087-4095, doi:10.5194/gmd-9-4087-2016.

Haensler, A., Saeed, F., Jacob, D. (2013). Assessing the robustness of projected precipitation changes over central Africa on the basis of a multitude of global and regional climate projections. Climate. Change, 121(2):349–363, doi: 10.1007/s10584-013-0863-8.

Häggmark, L., Ivarsson, K.-I., Gollvik, S., Olofsson, R.O. (2000). Mesan, an operational mesoscale analysis system. Tellus. Series A, Dynamic meteorology and oceanography, 52:2-20.

Hewitson, B.C., Daron, J., Crane, R.G., Zermoglio, M.F., Jack, C. (2014). Interrogating empirical-statistical downscaling. Climate. Change, 122(4):539–554, doi:10.1007/s10584-013-1021-z.

IPCC (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324.

Jones, P.W., (1999). First- and Second-Order Conservative Remapping Schemes for Grids in Spherical Coordinates. Mon. Wea. Rev., 127:2204-2210, doi:10.1175/1520-0493.

Jones, C., Giorgi, F., Asrar, G. (2011). The Coordinated Regional Downscaling EXperiment CORDEX, an international downscaling link to CMIP5. CLIVAR Exchanges 16:34-40.

Kalnay, E. (2002). Atmospheric Modeling, Data Assimilation and Predictability, Cambridge University Press.

Kim, J., Kim, T., Arritt, R., Miller, N. (2002). Impacts of increased atmospheric CO_2 on the hydroclimate of the Western United States. J. Climate, 15:1926–1942, doi:10.1175/1520-0442.

Klein Tank, A.M.G., Zwiers, F.W., Zhang, X. (2009). Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation, Climate data and monitoring WCDMP No.72, WMO-TD No. 1500, pp 56, http://www.wmo.int/pages/prog/wcp/wcdmp/wcdmp_series/documents/WCDMP_72_TD_1500_en_1.pdf (accessed February 2018).

Kobayashi, S., Ota, Y., Harada, Y., Ebita, A., Moriya, M., Onoda, H., Onogi, K., Kamahori, H., Kobayashi, C., Endo, H., Miyaoka, K., Takahashi, K. (2015). The JRA-55 Reanalysis: General Specifications and Basic Characteristics. J. Meteor. Soc. Japan, 93(10):5-48, doi: 10.2151/jmsj.2015-001.

Lee, J.W., Hong, S.Y. (2013). Potential for added value to downscaled climate extremes over Korea by increased resolution of a regional climate model. Theor. Appl. Climatol., 117(3-4):667–677, doi: 10.1007/s00704-013-1034-6.

Lindsay, R., Wensnahan, M., Schweiger, A., Zhang, J. (2014). Evaluation of Seven Different Atmospheric Reanalysis Products in the Arctic. J. Climate, 27:2588-2606, doi:10.1175/JCLI-D-13-00014.1

Liston, G.E., Hiemstra, C.A. (2011). The Changing Cryosphere: Pan-Arctic Snow Trends (1979-2009). J. Climate, 24(21):5691-5712, doi: 10.1175/jcli-d-11-00081.1.

Lorenz, C., Kunstmann, H. (2012). The Hydrological Cycle in Three State-of-the-Art Reanalyses: Intercomparison and Performance Analysis. J. Hydrometeor., 13:1397-1420, doi:10.1175/JHM-D-11-088.1.

Mahfouf, J.-F., Brasnett, B., Gagnon, S. (2007). A Canadian precipitation analysis (CaPA) project: Description and preliminary results. Atmos. Ocean, 45:1-17, doi:10.3137/ao.v450101.

Maraun, D. (2016). Bias correcting climate change simulations—a critical review. Curr. Clim. Change Rep., 2(4):211–220, doi:0.1007/s40641-016-0050-x.

Matsikaris, A., Widmann, M., Jungclaus, J. (2015). On-line and off-line data assimilation in palaeoclimatology: a case study. Clim. Past, 11:81-93, doi:10.5194/cp-11-81-2015.

McKenney, D. W., Hutchinson, M.F., Papadopol, P., Lawrence, K., Pedlar, J., Campbell, K., Milewska, E., Hopkinson, R., Price, D., Owen, T. (2011). Customized spatial climate models for North America. Bull. Amer. Meteor. Soc., (BAMS), 92(12):1612-1622, doi: 10.1175/bams-d-10-3132.1.

Mekis, E., Vincent, L. (2011). An Overview of the Second Generation Adjusted Daily Precipitation Dataset for Trend Analysis in Canada. Atmos. Ocean, 49(2):163-177, doi:10.1080/07055900.2011.583910.

Mudryk, L.R., Derksen, C., Kushner, P.J., Brown, R. (2015). Characterization of Northern Hemisphere Snow Water Equivalent Datasets, 1981-2010. J. Climate, 28(20):8037-8051, doi: 10.1175/jcli-d-15-0229.1.

Nie, S., Wu, T., Luo, Y., Deng, X., Shi, X., Wang, Z., Liu, X., Huang, J. (2016). A strategy for merging objective estimates of global daily precipitation from gauge observations, satellite estimates, and numerical predictions. Adv. Atmos. Sci., 33:889-904, doi:10.1007/s00376-016-5223-y.

Paeth, H., Mannig, B. (2012). On the added value of regional climate modeling in climate change assessment. Clim. Dyn., 41(3–4):1057–1066, doi: 10.1007/s00382-012-1517-7.

Panthou, G., Vischel, T., Lebel, T., Blanchet, J., Quantin, G., Ali, A. (2012). Extreme rainfall in West Africa: A regional modeling. Water Resour. Res., 48, W08501, doi:10.1029/2012WR012052.

Ren, L., Hartnett, M. (2017). Sensitivity Analysis of a Data Assimilation Technique for Hindcasting and Forecasting Hydrodynamics of a Complex Coastal Water Body. Comput. Geosci., 99:81-90, doi:10.1016/j.cageo.2016.10.012.

Rienecker, M.M., Suarez, M.J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M.G., Schubert, S.D., Takacs, L., Kim, G.-K., Bloom, S., Chen, J., Collins, D., Conaty, A., Da Silva, A., Gu, W., Joiner, J., Koster, R.D., Lucchesi, R., Molod, A., Owens, T., Pawson, S., Pegion, P., Redder, C.R., Reichle, R., Robertson, F.R., Ruddick, A.G., Sienkiewicz, M., Woollen, J. (2011). MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. J. Climate, 24(14):3624-3648, doi: 10.1175/jcli-d-11-00015.1.

Ruane, A.C., R. Goldberg, R., J. Chryssanthacopoulos,J. (2015). AgMIP climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation. Agr. Forest Meteorol., 200:233-248, doi:10.1016/j.agrformet.2014.09.016.

Ruest, B., Neumeier, U., Dumont, D., Bismuth, E., Senneville, S., Caveen, J. (2015). Recent wave climate and expected future changes in the seasonally ice-infested waters of the Gulf of St. Lawrence, Canada. Clim. Dyn., 46(1):449–466, doi:10.1007/s00382-015-2592-3.

Saha, S., Moorthi, S., Pan, H.-L., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., Liu, H., Stokes, D., Grumbine, R., Gayno, G., Wang, J., Hou, Y.-T., Chuang, H.-Y., Juang, H.-M. H., Sela, J., Iredell, M., Treadon, R., Kleist, D., Van Delst, P., Keyser, D., Derber, J., Ek, M., Meng, J., Wei, H., Yang, R., Lord, S., Van den Dool, H., Kumar, A., Wang, W., Long, C., Chelliah, M., Xue, Y., Huang, B., Schemm, J.-K., Ebisuzaki, W., Lin, R., Xie, P., Chen, M., Zhou, S., Higgins, W., Zou, C.-Z., Liu, Q., Chen, Y., Han, Y., Cucurull, L., Reynolds, R. W., Rutledge, G., Goldberg, M. (2010). The NCEP Climate Forecast System Reanalysis. Bull. Amer. Meteor. Soc., 91(8):1015-1057, doi: 10.1175/2010bams3001.1.

Saucier, F.J., Senneville, S., Prinsenberg, S.J., Roy, F., Smith, G.C., Gachon, P., Caya, D., Laprise, R. (2004). Modelling the sea ice-ocean seasonal cycle in Hudson Bay, Foxe Basin and Hudson Strait, Canada. Clim. Dyn., 23(3-4):303–326, doi:10.1007/s00382-004-0445-6.

Senneville, S., St-Onge Drouin, S. (2013). Étude de la variation des glaces dans le système couplé océan-glace de mer de la baie d'Hudson. Rapport préparé pour le ministère des transports du Québec. Rimouski, Institut des sciences de la mer de Rimouski, 63 p.

Sheffield, J., Goteti, G., Wood, E.F. (2006). Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling. J. Climate, 19(13):3088-3111, doi: 10.1175/jcli3790.1.

Shi, Y., Wang, G., Gao, X. (2017). Role of resolution in regional climate change projections over China, Clim. Dyn., First Online, doi:10.1007/s00382-017-4018-x.

Sillmann, J., Kharin, V.V., Zhang, X., Zwiers, F.W., Bronaugh, D. (2013). Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. J. Geophys. Res. Atmos., 118:1716-1733, doi:10.1002/jgrd.50203.

Soci, C., Bazile, E., Besson, F., Landelius, T. (2016). High-resolution precipitation re-analysis system for climatological purposes. Tellus A: Dynamic Meteorology and Oceanography, 68, 29879, doi:10.3402/tellusa.v68.29879.

Stern, G.A., Gaden, A. (2015). From Science to Policy in the Western and Central Canadian Arctic: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization. ArcticNet, Quebec City, 432 pp.

Taylor, K.E., Stouffer, R.J., Meehl, G.A. (2012). A Summary of theCMIP5 Experiment Design. Bull. Amer. Meteor. Soc., 93:485–498.

Thrasher, B., Maurer, E.P., McKellar, C., Duffy, P.B. (2012). Technical Note: Bias correcting climate model simulated daily temperature extremes with quantile mapping. Hydrol. Earth Syst. Sci., 16:3309-3314, doi:10.5194/hess-16-3309-2012.

Tustison, B., Harris, D., Foufoula-Georgiou, E. (2001). Scale issues in verification of precipitation forecasts. J. Geophys. Res., 106:11775-11784, doi:10.1029/2001JD900066.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Matsui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K. (2011). Representative concentration pathways: An overview. Climatic Change, 109:5-31, doi: 10.1007/s10584-011-0148-z.

Vincent, L.A, Wang, X.L., Milewska, E.J., Wan, H., Yang, F., Swail, V. (2012). A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis. J. Geophys. Res., 117, D18110, doi:10.1029/2012JD017859.

Vrac, M., Friederichs, P. (2015). Multivariate – Intervariable, Spatial, and Temporal – Bias Correction. J. Climate, 28:218-237, doi:10.1175/JCLI-D-14-00059.1.

Weedon, G.P., Balsamo, G., Bellouin, N., Gomes, S., Best, M.J., Viterbo, P. (2014). The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data. Water Resour. Res., 50:7505–7514, doi:10.1002/2014WR015638.

Williams, T.D., Bennetts, L.B., Squire, V.A., Dumont, D., Bertino, L. (2013a). Wave-ice interactions in the marginal ice zone Part 1: Theoretical foundations. Ocean Model., 71:81-91, doi:10.1016/j.ocemod.2013.05.010.

Williams, T.D., Bennetts, L.B., Squire, V.A., Dumont, D., Bertino, L. (2013b). Wave-ice interactions in the marginal ice zone Part 2: Numerical implementation and sensitivity studies along 1D transects of ocean surface, Ocean Model., 71:92-101, doi:10.1016/j.ocemod.2013.05.011.

Zou, H., Zhu, J., Zhou, L., Li, P., Ma, S., 2014. Validation and application of reanalysis temperature data over the Tibetan Plateau. Acta Meteorol Sin., 28:139-149, doi:10.1007/s13351-014-3027-5 91(8):1015-1057, doi: 10.1175/2010bams3001.1.

PUBLICATIONS

Langen, P.L., R. Brown, P. Grenier, C. Barrette, D. Chaumont, C. Derksen, J. Hamilton, T. Ingeman-Nielsen, S. Howell, T. James, D. Lavoie, S. Marchenko, S.M. Olsen, C.B. Rodehacke, M. Sharp, S.L. Smith, M. Stendel, and R.T. Tonboe, 2018: Baffin Bay and Davis Strait Regional Drivers of Change, Chapter 3 in Adaptation Actions for a Changing Arctic: Perspectives from the Baffin Bay-Davis Strait Region, Arctic Monitoring and Assessment Programme, (AMAP), Oslo, Norway.

L'Hérault E., Boisson A., Allard M., Aubé-Michaud S., Sarrazin D., Roger J., Barrette C. (2017). Détermination et analyse des vulnérabilités du Nunavik en fonction des composantes environnementales et des processus physiques naturels liés au climat: Phase 1. Centre d'études nordiques, Université Laval. 160pp.

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 Indigenous and Northern Affairs 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

Below we highlight some of our key findings in 2017:

- Most of the freshwater systems we studied 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 once again 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. This occurred even though spring/ summer 2017 was colder than other recent years, and as such, glacial melt was muted. CO_2 concentrations decreased with increasing distance from glacier termini, indicating active weathering of recently comminuted, geochemically active sediments.
- Although accelerated climate warming in the Arctic has, in general, greatly enhancing glacial melt in the Lake Hazen watershed, there is still year-to-year variation in the extent of melt, whereby in some year there is a net loss of glacial mass, and in other years, there is still a net gain of glacial mass. The annual net loss of glacial mass is obviously unsustainable in the long-term.
- Increased glacial runoff has reduced 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.
- Dense turbidity currents entering Lake Hazen from glacial rivers in high melt years rapidly deliver dissolved O_2, nutrients and suspended sediments to the 267 m depths of Lake Hazen.
- Snowpack depths in 2017 were average for the region, but there was a very delayed and slowed snowmelt due to cooler than normal temperatures.
- Differences between 'measured' and 'theoretical' values for stable carbon isotopes for DIC (δ^{13}C-DIC) in the glacial rivers indicated that changes in ^{13}C-DIC in glacial rivers are controlled by key environmental processes that require further understanding.
- Microbial community structure in snowpacks were different from those in snowmelt, which were different from those in glacial rivers, which were different from those in Lake Hazen.
- Dominant microbial phyla occurring within both Lake Hazen and glacial rivers include members from the Proteobacteria, Bacteroidetes and Cyanobacteria.
- Large amounts of dissolved O_2 were consumed under the ice in Skeleton Lake, suggesting high rates of microbial decomposition of organic matter in the sediments and water column of this smaller lake on the landscape.
- The microbial methylation of inorganic mercury (HgII) to the more toxic methylmercury (MeHg) form readily occurred under the ice and in the sediments of Skeleton Lake due to low levels of dissolve O_2 creating a suitable habitat for Hg methylating bacteria.
- In spring 2017 at the deepest point of Lake Hazen, dissolved O_2 concentrations started declining and CO_2 concentrations began increasing below 180 m depth due to active microbial metabolism in the sediments and no physical mixing of the water column under the ice. We also saw a peak in dissolved O_2 concentration just under the lake ice, coincident with a peak in Chl a concentrations, suggesting an early onset of primary productivity in the springtime.
- Dissolved O_2 was depleted within the top centimeter of sediments collected at five different sites in Lake Hazen in spring 2017, regardless of the depth from which sediments were collected, suggesting very active microbial respiration of organic matter in sediments. This respiration also consumed dissolved O_2 in certain deep and

shallow regions of the Lake Hazen water column, creating uninhabitable zones for Arctic Char.

- We have begun to identify the unique taxonomic distribution of the sediment microbial community at each of our five 2017 sediment sampling sites.
- We have begun quantifying the ~300-year paleoecological record of Lake Hazen using sediment cores collected at the two deepest, but separated, locations in Lake Hazen. Recent warming of the region and increased inputs of nutrients, contaminants, sediments, etc. into Lake Hazen have completely altered its limnological and biogeochemical state into something unprecedented for the past 300 years.
- The current ecological state of Lake Hazen is also totally unprecedented for the past 300 years.

RESEARCH OBJECTIVES

To examine coupled terrestrial-aquatic impacts of climate change on high Arctic watersheds, our research program had five specific objectives. We quantified:

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.

Specific emphasis was 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

- 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.
- Designed and built a small exhibit demonstrating climate change impacts on arctic freshwater cycles and subsequent impacts on downstream freshwater systems for the local Telus World of Science as part of a "research outreach" and public communication/education workshop. The display has been/will be shown over the course of a month for the general public.

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 at various times between 19 May and 28 July 2017 at Lake Hazen. During our time in the field, as well as outside the field season, we concentrated on addressing all five of the objectives of our research program, making sure to tie up any loose ends in our final year of ArcticNet funding.

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 spring/summer 2017, metabolism in Skeleton Lake was assessed under the lake ice and for part of the open water season by quantifying net primary productivity (NPP) of surface waters and lake respiration. A YSI EXO2 sonde with dissolved O_2, pH, conductivity, temperature and total algae sensors was deployed from mid-May to mid-July to obtain a continual record of these parameters during the transition from ice-cover to open water conditions in surface waters of Skeleton Lake. A chain of HOBO temperature loggers continuously recorded water temperature at discrete depths to resolve thermal stratification. Water column respiration rates were quantified using OxySense O2xyDot sensors and light/dark incubation bottles. General 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), as well as dissolved greenhouse gases (CO_2 and CH_4) concentrations, were also quantified at different depths in the Skeleton Lake water column. Meteorological instrumentation (anemometer, and PAR, air temperature and barometric pressure sensors) was also deployed during this time on the edge of Skeleton Lake (Wisniewski, Lehnherr).
- During July 2017, we completed a comprehensive spatial survey of the glacial rivers to determine whether the rivers are CO_2 sources or sinks to the atmosphere (Schiff, Dainard, St.Pierre, St.Louis, English).

Net mass change of glaciers in the Lake Hazen watershed

- In July 2017, we installed two additional high precision GPS units 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. In 2016, the two original GPS units were deployed near the margins of the Henrietta Nesmith and Gilman glaciers. In 2017, the two new units were deployed on a nunatak within the northern Ellesmere Icefield and near the Ruggles River outflow of Lake Hazen (Sharp, Dubnick, Danielson).
- We downloaded the data from the GPS units deployed in 2016 and serviced those units for another year of sampling (Sharp, Dubnick, Danielson).
- Watershed areas for each of the glaciers (sub-watersheds) were delineated from the 1:50000 Canadian Digital Elevation Model (CDEM; Natural Resources Canada) in ArcGIS 10.5. Daily glacial run-off (kg m^{-2} d^{-1}) was modeled using a surface mass balance approach within each sub-watershed [13], where run-off was calculated as the difference between daily melt and re-freeze. This extended our modelled mass-balance estimates to the end of 2016. These modelled discharge data will also be compared with the periodically measured discharge at the gauged Ruggles River station (Gardner, St.Pierre, Water Survey Canada).

Chemical inputs to Lake Hazen from snowmelt, glacier melt and soil/permafrost thaw

- Snow was collected in May 2017 from five sites on the surface of Lake Hazen, and from five sites on the nearby landscape. Areal water volume of the snowpacks was also quantified at each site. Snow samples were analysed for microbial community structure, general chemical parameters as described above and mercury (methylmercury [MeHg], total mercury [THg]) (Lehnherr, St.Louis, Cavaco, Wisniewski, Varty).
- Snowmelt was collected in June 2017 from Blister Creek, the Abbé River and Skeleton Creek near where they entered Lake Hazen. As with snow samples, snowmelt samples were analysed for microbial community structure, general chemical parameters and MeHg and THg (Lehnherr, St.Louis, Cavaco, Wisniewski, Varty).
- In May 2017, rates of Hg methylation and demethylation were quantified in: 1) the Skeleton Lake water column, 2) Skeleton Lake sediments, and 3) local snowpacks, using stable Hg isotope incubation experiments to determine hotspots of net MeHg production on Arctic landscapes (Varty, Lehnherr).
- 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, in late May/early June 2017 and mid-late July 2017, samples were taken for general water chemistry, suspended sediments, DOC quality, ^{14}C-DOC, stable isotopes (e.g., 3H, $\delta^{18}O$, $\delta^{2}H$-H_2O, SO_4^{2-}, and $\delta^{34}S$- SO_4^{2-}) and greenhouse gas concentrations to determine how the different landscape features impacted biogeochemical processes (Schiff, Dainard, English).
- Between 6-28 July 2017, we accessed glacial inflow rivers (Abbé, Gilman, Henrietta Nesmith, Very, Turnabout, Snowgoose, Blister) as well as the outflow Ruggles River to sample for general water chemistry, suspended sediments, DOC quality, ^{14}C-DOC, stable isotopes (e.g., 3H, $\delta^{18}O$, $\delta^{2}H$-H_2O, SO_4^{2-}, and $\delta^{34}S$- SO_4^{2-}), greenhouse gas concentrations and microbial community composition. A special focus was placed on DOC and dissolved inorganic carbon (DIC) dynamics in glacial river systems emptying into Lake Hazen to assess processes that are instrumental in determining the sources/sinks of these analytes and biogeochemical implications for glacial melt water impacted systems in the high Arctic. This was done in cooperation with Parks Canada and Environment and Climate Change Canada, who concurrently sampled four of the rivers (Turnabout, Very, Abbé, Ruggles) 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 (Schiff, Dainard, English, Cavaco, St.Louis).

The metabolism of Lake Hazen itself

- Water column chemistry: We measured freshwater quality in Lake Hazen by conducting a water column profile at the deepest point of the lake (267 m) in May 2017. This sampling extended our long-term sampling of Lake Hazen, which began in 2012, by another year. From a hole in the lake ice, we first deployed a YSI EXO_2 sonde with dissolved O_2, pH, conductivity, temperature and total algae sensors. We then sampled water using a cleaned 12 L Niskin bottle at our now standardized 15 depths for the complete suite of water chemistry as described above for snow, snowmelt, glacial river and Skeleton Lake chemistry, as well as microbial community composition (St.Louis, Lehnherr, Cavaco, St.Pierre, Talbot).
- Sediment microbial processes and diversity: We used UNISENSE microelectrodes (O_2, pH and redox) to examine microprofiles of redox-related biogeochemical processes in sediment cores

collected from five sites, ranging in depths and strategic locations, from Lake Hazen in May/June 2017. 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 (OC, N, P, C) analyses. Companion cores from each of the five sites were collected to extract and sequence the DNA and RNA from each site, and perform metagenomics analysis on the DNA sequences using multiple bioinformatics approaches to classify the taxonomy and functional potential of the lake sediment ecosystems (Poulain, Colby, St.Pierre, St.Louis, Ruuskanen).

Long-term biological and biogeochemical changes in Lake Hazen and its watershed using sediment cores

- Sediments: We collected four intact sediment cores from the main deep site of Lake Hazen (265 m) and three intact sediment cores from the secondary deep site of the lake (260 m) in May/June 2017 while there was still ice on the lake. The cores were quickly returned to the Lake Hazen field laboratory, where they were sectioned into either 0.5 cm sections (top 20 cms) and 1.0 cm sections (below 20 cms). Sections were placed into clean containers and immediately frozen. Sediments are now being processed for ^{210}Pb dating, diatom enumeration, and geochemical and contaminant concentrations.

RESULTS

Below we highlight some of our findings to date. However, analyses are still being completed for some of our activities, and results are not yet available.

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).

- Prior to ice breakup in spring 2017, Skeleton Lake's total water column volume beneath the ice consumed 2.6 kg of dissolved O_2 between 20-May and 4-June. This translated to a below ice respiration rate of 1.22 mg O_2 L^{-1} d^{-1}, suggesting very high rates of microbial decomposition in the organic rich (~25% organic carbon) sediments of the lake. Ice breakup occurred between 18-24 June, with the open water season commencing on 29-June.
- Glacial rivers were under-saturated with respect to CO_2 in July 2017 due to geochemical weathering reactions occurring in the rivers. Decreases in dissolved CO_2 over space were mirrored by increases in dissolved chemical constituents that are indicators of active geochemical weathering. However, the glacial rivers were less undersaturated in CO_2 in 2017 than in 2016 because glacial melt was less intense in the colder 2017 spring/summer (St. Pierre, Dainard, Schiff, St.Louis).

Net mass change of glaciers in the Lake Hazen watershed

- All four glacier GPS units are now collecting data. We are also beginning to process the GPS data that was collected from the two GPS units deployed in summer 2016 near the margins of the Henrietta Nesmith and Gilman glaciers (Sharp, Dubnick, Danielson).
- Modelled annual water discharge from the main glacial river subcatchments in the Lake Hazen watershed show major interannual variation dependent on summer near surface air temperatures (Figure 1). Ruggles River discharge outflow volume measurements are still being quality controlled by Water Survey Canada (Gardner, St.Pierre, Water Survey Canada).

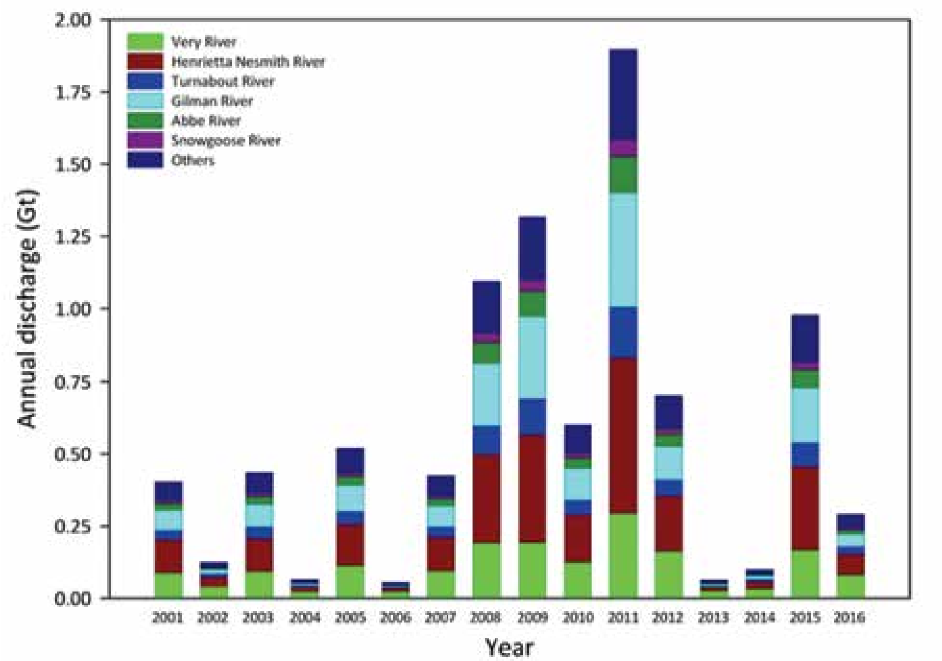

Figure 1. Modelled annual water discharge from the main glacial river subcatchments in the Lake Hazen watershed, 2001-2016.

Chemical inputs to Lake Hazen from snowmelt, glaciermelt and soil/permafrost thaw

- Although all the glacial river water samples have already been analysed for all general water chemistry parameters, we are still in the process of interpreting the results relative to those obtained in the summers of 2015 and 2016 (Schiff, Dainard, English, Cavaco, St.Pierre, St.Louis).
- Our understanding of the chemical characterization of DOC was enhanced using analytical techniques that highlighted DOC compositional variability in glacial river systems. Deviance of 'measured' vs. 'theoretical' values for stable carbon isotopes for DIC ($\delta^{13}C$-DIC) have indicated that changes in ^{13}C-DIC in glacial rivers are likely controlled by key environmental processes that require further understanding (Dainard, Schiff, English).
- Snow packs in the Lake Hazen watershed contain elevated concentrations of MeHg (0.53 ng/L), with the majority of the MeHg being particulate bound.
- MeHg concentrations in the Skeleton Lake water column in May 2017 (0.54 ng/L) were eight times higher than concentrations in the water column in summer 2016 (0.068 ng/L), indicating that Hg methylation under ice over the winter and in spring may be a significant source of MeHg to the Skeleton Lake continuum.
- All freshwater compartments sampled within the Lake Hazen watershed contained their own unique microbial communities (e.g., microbial communities in snow were distinct from the microbial communities in snowmelt which were distinct from those in the glacial rivers). Dominant microbial phyla occurring within both Lake Hazen and glacial rivers include members from the Proteobacteria, Bacteroidetes and Cyanobacteria. While the Lake Hazen microbial communities were also comprised of these dominant phyla, certain classes, families and species within these phyla were significantly distinct within the Lake Hazen microbial community, with members from the phylum Elusimicrobia being more prevalent (within top

three phyla) than their counterparts in glacial river input.

The metabolism of Lake Hazen itself

- Water column chemistry: Water column chemistry in Lake Hazen measured under the ice in May 2017 was similar to that measured under the ice in the springs of 2012, 2013, 2014 and 2015. For example, following winter, we typically find that below 180 m, dissolved 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. Concentrations of NO_2+NO_3 and SO_4^{2-} increase in the deeper parts of the watercolumn. We also tend to see a peak in dissolved O_2 concentrations just under the lake ice, coincident with a peak in Chl a concentrations, suggesting an early onset of primary productivity in the springtime (St.Louis, St.Pierre, Lehnherr, Talbot).
- The microbial community structure within Lake Hazen is maintained over spring and summer seasons, despite large glacial inputs, with their own unique microbial community compositions, occurring during the summer (Cavaco, St.Louis).
- Sediment microbial processes and diversity: At 4 of the 5 sites we sampled, dissolved O_2 was depleted within the first centimeter of the surface of the sediments, suggesting very active microbial respiration. This microbial activity was likely fueled by organic carbon that entered the lake in glacial runoff the previous summer. Microbial respiration at most of these sites was strong enough to also consume oxygen in the overlying water. At the 5th site, a shallow site near the outflow of the lake that has very little organic carbon content, oxygen penetrated the sediments much deeper. Our earlier work using high-throughput amplicon sequencing of the 16S rRNA gene uncovered a sediment microbial community dominated by Proteobacteria, Bacteroidetes, and Chloroflexi, similar to those found in other cold and oligotrophic lake sediments. More critically, whereas Lake Hazen sediments had phylogenetically distinct communities shaped by pH and redox gradients, we found evidence for functional redundancy. We have begun to identify a unique taxonomic distribution of organisms at each of our five new sampling sites, indicating the potential for a diversity of microorganisms to thrive (Poulain, Colby, St.Pierre, St.Louis, Ruuskanen).

long-term biological and biogeochemical changes in Lake Hazen and its watershed using sediment cores

- Sediment cores from the two deepest sites in the lake are currently being processed and analysed, so unfortunately, we have no results to report at this time.

DISCUSSION

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).

- 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.

Net mass change of glaciers in the Lake Hazen watershed

- The glaciers in the Lake Hazen watershed have generally been melting more rapidly than in the past due to increases in near surface temperatures from human-induced climate warming. In some of the warmer years, the glaciers are annually losingmore mass than they are gaining. However, there is still large year-to-year variation in the amount of melt that is occurring.

Chemical inputs to Lake Hazen from snowmelt, glacier melt and soil/permafrost thaw

- The hydrology of Lake Hazen is driven primarily by inputs from the glacial rivers, and to a much, much lesser extent, from small permafrost thaw streams like the Skeleton Lake continuum. As such, chemical inputs to the Lake Hazen, as well as the water residence time of Lake Hazen, are largely a function of glacial melt in any given year and the magnitude of erosion in the river valleys before the water enters Lake Hazen, which effects the delivery of glacial sediment, nutrients, OC and legacy contaminants to Lake Hazen. Accelerate climate warming in the Arctic is accelerating rates of glacial melt, which in turn is greatly impacting the physical and chemical properties of Lake Hazen.

The metabolism of Lake Hazen itself

- Increased inputs of nutrients and organic carbon to Lake Hazen due to increased glacial melt, along with the fact that Lake Hazen is now going ice-free almost every summer (something that only occasionally happened in the past), is increasing both primary production in the water column and heterotrophic respiration in the lake sediments. In fact, heterotrophic respiration in the sediments consumes so much oxygen in the overlying water over the winter, making parts of Lake Hazen uninhabitable for the only fish species in the lake (Arctic Char).
- Glacial run off, summer season (whether early or late summer) and location sampled only explain 3% of the total variance seen within glacial and Lake Hazen microbial communities. This suggests that the long residence time of water within Lake Hazen may be a major factor in selecting for microbial communities passively delivered by glacial input into the Lake Hazen water column. This is evidenced by the fact that communities sampled from glacial river mouths are significantly different from Hazen moat samples, which are significantly different from samples taken from the water column at depth, both in the spring and the summer (with also significantly decreased diversity, with respect to glacial samples). The fact that Ruggles River outflow waters have communities that are overwhelmingly similar to Lake Hazen samples at depth indicates that the microorganisms introduced into Lake Hazen undergo selection (likely along temperature/O_2 gradients in the spring and turbidity in the summer). How stable the Lake Hazen water column microbial community is from the spring ice to summer melt season is the next question to answer, especially in the face of increasing Arctic temperatures and glacial melt.

Long-term biological and biogeochemical changes in Lake Hazen and its watershed using sediment cores

Once the sediment cores have been analysed, they will provide us with an ~300-year integrated paleoecological record for Lake Hazen and its watershed, including changes that have occurred naturally in the past, and more recently, due to human activities on the planet, such as global warming and the release of contaminants to the atmosphere. We are also looking forward to understanding how the watershed has changed since we last collected and analysed sediment cores in 2013, and if the newer sediment record reflects the data we collected in the Lake Hazen watershed and Lake Hazen itself over the past three years (see above).

CONCLUSION

We are still in the early days of synthesizing a watershed-scale interpretation of the coupled terrestrial-aquatic impacts of climate change on high Arctic watersheds using the new data we collected during the three-year tenure of our ArcticNet funding. Some of our earlier and broader syntheses, using a combination of historical, contemporary, modelled and paleolimnological datasets, found that Lake Hazen had already 'succumbed' to climate warming with only a ~1°C relative increase in recent summer air temperatures. This warming deepened the active layer of soils and triggered large mass losses from the watershed's glaciers, resulting in an ~10-times increase in delivery of glacial meltwaters, sediment, organic carbon and legacy contaminants to Lake Hazen, a >70% decrease in lake water residence time, and near certainty of summer ice-free conditions. Concomitantly, the community assemblage of diatom primary producers in the lake shifted dramatically with declining ice cover, from shoreline benthic to open water planktonic species, and the physiological condition of the only fish species in the lake, Arctic Char, declined significantly. Collectively, these changes placed Lake Hazen in a biogeochemical, limnological and ecological regime unprecedented within the past ~300 years. The data we collected over the past three years will help us to: 1) better understand the specific mechanisms behind some these changes, 2) provide exciting results in new avenues of research, 3) set the baseline for which data can be compared to in all future research/monitoring activities, and 4) guide future research directions for further understanding of the coupled terrestrial-aquatic impacts of climate change on high Arctic watersheds.

PUBLICATIONS

Igor Lehnherr, Vincent L. St. Louis, Martin Sharp, Alex S. Gardner, John P. Smol, Sherry L. Schiff, Derek C. G. Muir, Colleen A. Mortimer, Neil Michelutti, Charles Tarnocai, Kyra A. St. Pierre, Craig A. Emmerton, Johan A. Wiklund, Günter Köck, Scott F. Lamoureux & Charles H. Talbot. The world's largest High Arctic lake succumbs to climate warming. NATURE Commmunications (Accepted Jan. 2018).

Matti O. Ruuskanen, Kyra A. St.Pierre, Vincent L. St.Louis, Stéphane Aris-Brosou and Alexandre J. Poulain. Evidence of functional redundancy in the sediment microbial communities of Lake Hazen, Nunavut, Canada. Frontiers in Microbiology (Submitted Jan. 2018).

IMPACTS OF THE CHANGING GLOBAL ENVIRONMENT AT NUNAVUT'S NORTHERN FRONTIER

Project Team

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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. This project aims to track and evaluate the environmental changes taking place along the northern coastline of Ellesmere Island, in Quttinirpaaq National Park and adjacent areas: Nunavut's northern frontier. Specific objectives include monitoring of climate, snow and permafrost ground temperatures; observations to determine changes in lake ice, alpine glaciers and the Milne Ice Shelf; mapping of surface motion for glaciers and ice caps; analysis of ice island production, drift and decay as marine hazards; and analysis of lake and fiord sediments to assess long term variability. Biological studies will include molecular analysis of microbial communities, including the biodiversity of their viral assemblages, and evaluation of trophic relationships in the lower food web of lakes and fjords of the region, with comparative studies at reference sites elsewhere in the Canadian North. All available information will be synthesized as a sub-regional impact study that can be used in climate assessments.

KEY MESSAGES

- Our ArcticNet research has shown that the northern coast of Ellesmere Island is a strategic site for the detection and analysis of Arctic environmental change given the diversity of freshwater and marine ecosystems, their extreme sensitivity to perturbations of the cryosphere (snow and ice-containing environments), and the polar amplification of global warming at these far northern latitudes (82-83°N).
- ArcticNet support has allowed us to produce a unique 14-year record of climate and permafrost at the world's most northerly land-based monitoring site: the northern frontier of Nunavut. It is difficult to see how this increasingly valuable record could be continued in the absence of ArcticNet or equivalent support.
- These far northern ecosystems are vulnerable to global change. Our results published in 2017 from Milne Fiord, for example, show large changes in the depth of the epishelf lake, and this ecosystem, the only one left of this type in the Northern Hemisphere, is now on the brink of extinction.
- We continued our extensive measurements of snow physical properties at the Ward Hunt Island monitoring site, which show how snow properties are unique to polar desert and affect the ground thermal regime.
- Our work published in 2017 revealed hidden biofilms on the bottom of Nunavut's most northerly lake: Ward Hunt Lake. These biofilms appear to produce methane in winter, indicating a shift towards greenhouse gas production as northern lakes continue to warm and retain liquid water at their base during winter. These results generated considerable media interest.
- Our ongoing molecular analysis of Northern Frontier samples of aquatic viruses has uncovered novel groups that occur in high abundance in northern waters and that may play a key role in food webs and nutrient recycling.
- Our work continues to show that land-terminating glaciers in the Canadian High Arctic have undergone a marked slowdown in their surface motion over the past 50+ years, particularly in their ablation areas, as illustrated by the White Glacier, Axel Heiberg Island.
- Our season of related field work at Ekaluktutiak (Cambridge Bay) by the Northern Frontier team was completed with success in 2017 and allowed opportunities for community outreach, youth mentorship and training of community members in freshwater monitoring.
- Our successful expedition to the remote, previously unexplored Stuckberry Point region of Northern Ellesmere Island in 2017 revealed lakes encompassing different productivities, and the unexpected presence of fish and benthic animal populations.
- Our high-precision surveys continue of ice islands, iceberg sails and keels in the Baffin Bay region.
- We now have a unique 11-month long ice island dataset from Baffin Bay, which revealed 5 m of thinning of ice thickness.

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 thermal 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, with comparative analyses at Ekaluktutiak.
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. This year we published a new, extensive compilation of organic carbon data from lakes and ponds throughout the circumpolar North (Wauthy et al. 2017).
- Public lectures in Canada, often with senior Canadian policy makers present (e.g. to the Senate Committee on Energy, Natural Resources and Environment; to Natural Resources Canada and NRC senior policy makers), with outreach lectures locally and abroad.
- Worked closely with the Inuit community of Ekaluktutiak (Cambridge Bay) in outreach (Figure 1), youth mentorship and training for freshwater monitoring.
- Many presentations at scientific conferences, plus symposium organisation.
- Various interviews with online, print and broadcast media (e.g. CBC Radio, online interviews, such as with 'Arctic Deeply').
- 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. Warwick Vincent has been aslked to sit on the Parks Canada Strategic Management Plan Committee for Quttinirpaaq National Park.
- Presented and discussed our work at the international forums, including at the meeting of the International Arctic Science Committee

Figure 1. Milla Ratio (Northern Frontier NI) running an outreach event on freshwater science at Ekaluktutiak, Nunavut. Photo credit: M. Rautio/CEN.

(IASC) in Prague (Vincent is the Canadian delegate for the terrestrial working group and former international vice chair of the TWG) and at an IASC Glaciology meeting in Austria (Copland).

- Participated in the ArcticNet meeting "Arctic Change" at many levels, from oral presentations and posters to organisation of a symposia (COA01 - Glacier Change and Ice-Ocean Interaction, co-chaired by Derek Mueller and Luke Copland; and ECO09 - Rapid Changes in Extreme Environments: the High Arctic co-chaired by Greg Henry and Warwick Vincent on the High Arctic), plus helped organize a Northern Infrastructure symposium SUD04. Toward a Strategy to Address Cumulative Effects of Rapid Arctic Transitions due Infrastructure and Climate (RATIC), co-chaired by Peter Schweitzer (University of Vienna), Andrey Petrov (University of Northern Iowa) and Elena Kuznetsova (Norwegian University of Science and Technology). Also convened and chaired an international planning workshop as an Arctic Change side meeting: Terrestrial Multidisciplinary Distributed Observatories for the Study of Arctic Climate (T-MOSAiC, 11 December 2017).
- Produced a summary of our glaciological results for the Eastern IRIS report, for Chapter 3 entitled 'Glaciers, Ice Shelves and Ice Islands', including co-authorship by Luke Copland, Derek Mueller, Warwick Vincent and several of our ArcticNet-supported graduate students.

INTRODUCTION

This project continues our work 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 14 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. 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 (Figure 2), 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

Figure 2. ArcticNet-Northern Frontier sampling in Disraeli Fjord, opposite Ward Hunt Island. This photograph was selected as the cover image for the 2018 Polar Continental Shelf Program (PCSP) calendar. Photo credit: D. Sarrazin/CEN.

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., 2017).

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 using remote sensing, improving the detection of ice islands using polarimetric synthetic aperture radar and examining the ecological implications of ice islands.

To understand the patterns and causes of iceberg and ice island production processes, we also need to understand how the glaciers are changing over time. Our ongoing work has identified reductions in glacier input to the ice shelves of northern Ellesmere Island over the past 50+ years (Mortimer et al., 2012; White et al., 2015), together with rapid recent acceleration of tidewater glaciers on SE Ellesmere Island (Van Wychen et al., 2016). For land-terminating glaciers, our work is continuing the long-term mass balance monitoring program at White Glacier, Axel Heiberg Island, which includes the provision of data annually to the World Glacier Monitoring Service as part of the Global Terrestrial Network for Glaciers, run by the World Meteorological Organization.

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.

Thick biofilms (microbial mats) dominated by cyanobacteria occur in marine and freshwater habitats, and are especially well developed in extreme aquatic environments, including in the Canadian High Arctic. These biofilms have a complex structural organisation that facilitates nutrient recycling, and they often dominate ecosystem biomass and biological production in the shallow lakes and ponds that are a major feature of the Arctic landscape. Although many of these high latitude water bodies freeze to the bottom during winter darkness, recent climate warming has led to reductions in bedfast ice, allowing microbial communities to persist in liquid water throughout the year. Part of our Northern Frontiers research focuses on these biological communities, and one of our aims in 2017 was to publish our work on how this transition from seasonally frozen to perennially unfrozen conditions might affect the microbiome structure of Arctic biofilms, and the associated potential for biogeochemical processes.

ACTIVITIES

We completed a partially successful season of field work along the northern coast of Ellesmere Island, and most objectives were completed. Bad weather hindered the planned helicopter operations off Ward Hunt Island, but all other operations proceeded as planned at Stuckberry Point (Antoniades) and Milne Fjord (Mueller and Copland), with ancillary work at the White Glacier, Ekaluktutiak (Rautio) and Whapmagoostui-Kuujjuarapik (Vincent), all as planned.

We continued the snow project at Ward Hunt Island in June-July 2017, and downloaded our Ward Hunt Island monitoring station data, including from our thermal conductivity data loggers (Figure 3).

We continued our long term measurements of permafrost monitoring and automated cameras on Ward Hunt Island in July 2017, 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.

We recovered instruments that have been recording temperature, oxygen, underwater light and chlorophyll fluorescence in Ward Hunt Lake, and continued our water column profiling and sampling in this lake (Figure 4). Time-lapse cameras were downloaded and serviced to provide monitoring of Disraeli Fiord, Ward Hunt Lake the Milne Glacier and floating ice tongue, and to monitor ice shelf breakups in our absence.

From July 9th to July 31st 2017, a four-person team carried out oceanographic, hydrological and glaciological measurements on the Milne Ice shelf and Milne Glacier in Milne Fjord, located on the northern coast of Ellesmere Island. This team of international collaborators was comprised of team lead Andrew Hamilton (Postdoctoral fellow, Carleton University), Peter Wray (masters Student, University of Waterloo), Drew Friedrichs (PhD student, University of California – Davis) and Jinksuk Kim (Research

Figure 3. The Ward Hunt Island instrument array being downloaded in July 2017. This is the northernmost land-based climate and permafrost monitoring station in the world, thanks to support from ArcticNet and partners. Photo credit: W. F. Vincent/CEN.

Figure 4. Sampling of ice-covered Ward Hunt Lake in 2017 by the ArcticNet Northern Frontier team (left) and the in situ instrumentation recovered from the lake in 2017 for redeployment in 2017/18 (right). Photo credits: W. F. Vincent/CEN.

Technician, Korean Polar Research Institute). This effort was part of a Polar Continental Shelf Program Arctic-Antarctic exchange. Based out of a camp on the outer Milne Ice Shelf, the team concentrated on a detailed investigation of a channel carved upward into the base of the ice shelf by warm freshwater. This channel was identified during previous years' fieldwork at the site. This year, the team aimed to drill a large hole through the ice shelf into the channel with a hot water drill, in order to be able to deploy a remotely-operated vehicle (ROV) and sonar in the channel with the aim of measuring melt in the channel and to determine whether the ice shelf is grounded on the seabed in the vicinity of the channel. Ice shelf thickness data were gathered using Ice Penetrating Radar. The team also recovered instruments that have been recording temperature and salinity of the water column within the channel since summer 2015, and deployed a high-resolution current meter and instruments measuring water temperature and salinity in the channel through this hole for 33 hours.

Based out of Purple Valley at the rear of the Milne ice shelf, we recovered instruments that recorded temperature and salinity in Milne Fiord over winter and re-deployed these (and additional instruments) to continue monitoring changes in the fjord for another year. These data have been collected since 2011 and represent a unique and valuable dataset, since the ice-shelf dammed freshwater lake at the rear of the ice shelf (an 'epishelf lake') is the last remaining in the Northern Hemisphere.

On Milne Glacier, the team installed four seismic stations for 11 days, consisting of seismometer and GPS units, in order to investigate glacier velocity and investigate the possibility of 'ice quakes' on the glacier. They also re-measured and maintained a network of ablation stakes drilled into the ice; revisiting these stakes year after year allow us to monitor surface melt on the glacier and ice shelf.

Two trips to White Glacier, Axel Heiberg Island were undertaken in 2017, in the spring and summer. The spring trip had good weather, which enabled the measurement of the glacier's mass balance stake network, downloading of existing weather stations, and the installation of new thermistor chains to a depth of ~15 m to assess long-term changes in the surface temperature regime of the glacier. A trip was also undertaken in July 2017, but long periods of bad weather and snow restricted helicopter availability. This meant that only basic measurements and instrument servicing could be made, but all of the essential work was still able to be completed. This included the downloading of three time-lapse cameras overlooking the termini of Good Friday and Iceberg glaciers to monitor their iceberg calving patterns.

In July 2017, we used the *Amundsen* to deploy 15 iceberg tracking beacons across northern Baffin Bay, and to service instruments on and around Trinity Glacier, SE Ellesmere Island. Air photo surveys of glaciers on SE Devon Island were also undertaken to monitor their long-term changes in volume, as part of a joint project funded by the UK Natural Environment Research Council.

Field data collection for a project investigating the utility of uninhabited aerial vehicles (UAVs) for mapping sea-ice topography was conducted on Frobisher Bay from May 4th to 20th by Martin St. Amant (Masters student, Carleton University) and Adam Garbo (research assistant, Carleton University). The team surveyed sea ice using a UAV equipped with a digital camera and high-precision GPS unit. These photos can be analyzed using Structure-from-Motion (SfM) photogrammetry to create 3D point clouds of the ice surface topography. Surveys aimed to capture a diversity of sea-ice features, such as level ice, pressure ridges, and structures caused by tidal deformations, under various lighting conditions, heights and camera settings. A ground-based survey was also completed, to serve as a comparison to data from the aerial surveys.

Jill Rajewicz (research associate, Carleton University) joined Leg 2b of the CCGS *Amundsen* scientific cruise from July 13 to August 1st with the aim of visiting the ice island that PhD candidate Anna Crawford has been studying, which was grounded near Qikiqtarjuaq, in Baffin Bay. Jill also was to deploy satellite tracking beacons on ice islands in Baffin Bay. The objective of this work is to better understand the drift and deterioration of ice islands, which present potential hazards to shipping and natural resource exploration in the Canadian Arctic and sub-Arctic, which will allow for accurate size and location prediction and improved risk assessment by stakeholders. Unfortunately, on the day scheduled for work on and around the ice island, conditions and visibility were too poor to fly from the ship to the ice island on the day, so no on-ice work was completed.

RESULTS

Key Milestone

One of our key milestones for 2017-18 was: 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. We are delighted to report that the publication of the final printed version of this monograph was in May 2017 (Figure 5).

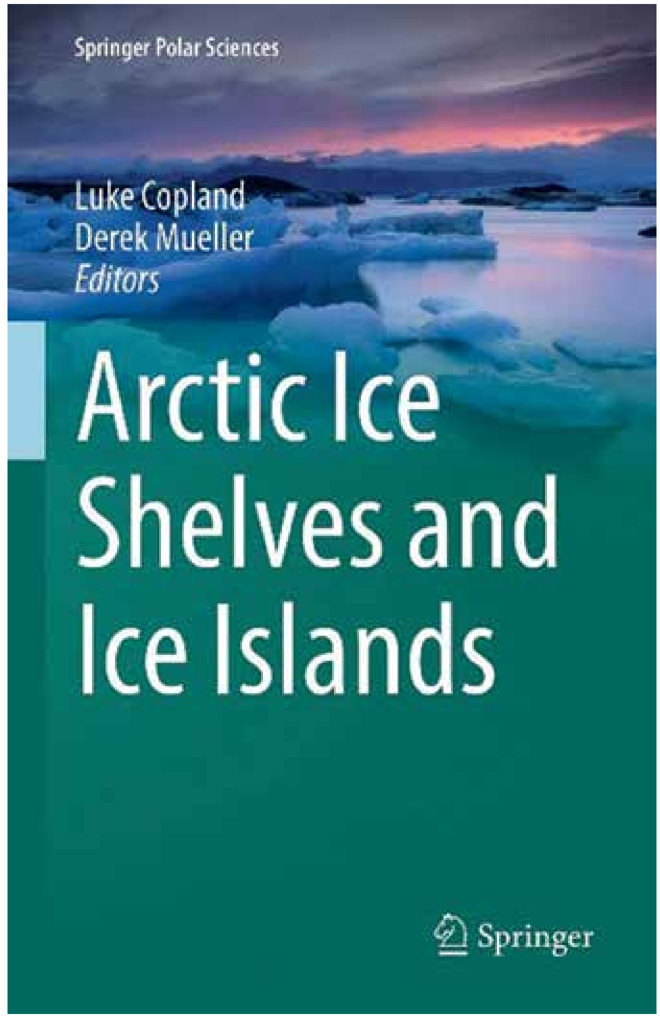

Figure 5. Synthesis monograph on Northern Ellesmere ice shelves edited by two ArcticNet Northern Frontier NIs and published in 2017 (Book image credit: Springer website).

Climate Monitoring

The 2017 summer season was similar to 2016, and we suspect there will be ongoing large changes in the ice-dependent environments of the region. RADARSAT data in 2016 indicated open water conditions in Disraeli Fjord (after we left) and large areas of open water in Ward Hunt Lake, and this was confirmed by our camera downloads in 2017. We installed a new camera system at Ward Hunt Lake in 2017 to capture these shifts with high resolution, as planned and noted in our 2016 report.

Cryosphere and paleolimnological measurements

Milne Fjord continued to show evidence of recent 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.

The recently completed MSc of Abigail Dalton provides the most comprehensive study to date of the patterns and causes of iceberg production events from Prince of Wales Icefield, Ellesmere Island. From an analysis of >8000 SAR images, it is clear that 4 tidewater glaciers (out of ~40) account for >90% of all iceberg production from this icefield and that there is a strong connection between the timing of iceberg events and sea ice conditions. Timelapse cameras at Trinity Glacier, SE Prince of Wales Icefield, also provide detailed information about iceberg calving at the fastest-flowing glacier in the region. These showed a terminus retreat of ~2 km in both summer 2016 and summer 2017 due to calving, but a somewhat unexpected readvance of the terminus by ~1 km in winter 2016/2017 as sea ice is present to hold the glacier ice in place. Ongoing work is investigating this further, including a visit on the *Amundsen* in summer 2018. In the paleolimnological part of our project, four sediment cores were successfully obtained from the remote Stuckberry Point lakes and stratigraphic analyses are currently underway.

Microbial network characterization

Sampling was only partially completed (because of bad weather for helicopter flying) for microbial DNA analysis. ArcticNet postdocs continued to develop and apply protocols for microbial network analysis; former ArcticNet postdoc Jérôme Comte (now tenure-track Professor at INRS) continues to analyze the molecular data from Ward Hunt Island and a manuscript is now under revision with a Nature journal. New analyses are now being applied by postdoc Adrien Vigneron, with comparative analysis of samples from our sites at Kuujjuarapik that have revealed new lineages of bacteria. Our collaborators have also isolated new microbes from our Northern Frontier samples (Tsuji et al. 2107a,b).

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. In 2017-2018, we are in the process of completing our analyses of data from Lake A. Lake A is a meromictic lake consisting of a freshwater surface layer fed by the spring run-off of the surrounding catchment, overlying ancient seawater that was trapped by isostatic rebound several thousand years ago. This salt water layer is particularly resistant to mixing and its physical and chemical conditions are very stable. Our data suggests that the viral community structure of Lake A changes with depth and that the freshwater layer and the ancient seawater layer are strikingly distinct indicating important differences in their viral sequence composition (Figure 6). Our ongoing analyses include the classification of these sequences and the identification of viral genes of ecological importance. In addition, the inoculation of cyanobacteria cultures with enriched virus communities from our three primary sampling sites (Ward Hunt Lake, Lake A and Milne Fiord) has resulted in several candidate viruses. We have sequenced one of these viruses and will continue the

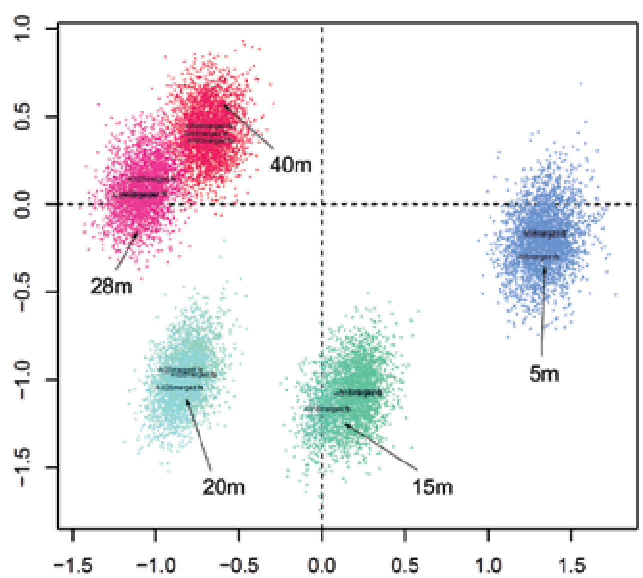

Figure 6. Clustering of viral communities from different depths in Lake A. The samples were collected in triplicates and analyzed as individual samples. (Culley laboratory, unpublished).

process of isolating and amplifying the remaining promising candidates in preparation for sequencing.

The inoculation of cyanobacteria cultures with enriched virus communities from our three primary sampling 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.

Microbial biofilms

Our work on biofilms (as described above) continued and part of the Northern Frontier work culminated in a published article that drew considerable. Interests. This study led by Northern Frontier postdoc Vani Mohit showed the striking contrasts in taxonomic and functional diversity the shallow versus deep-water biofilms of Ward Hunt Lake (Figure 7).

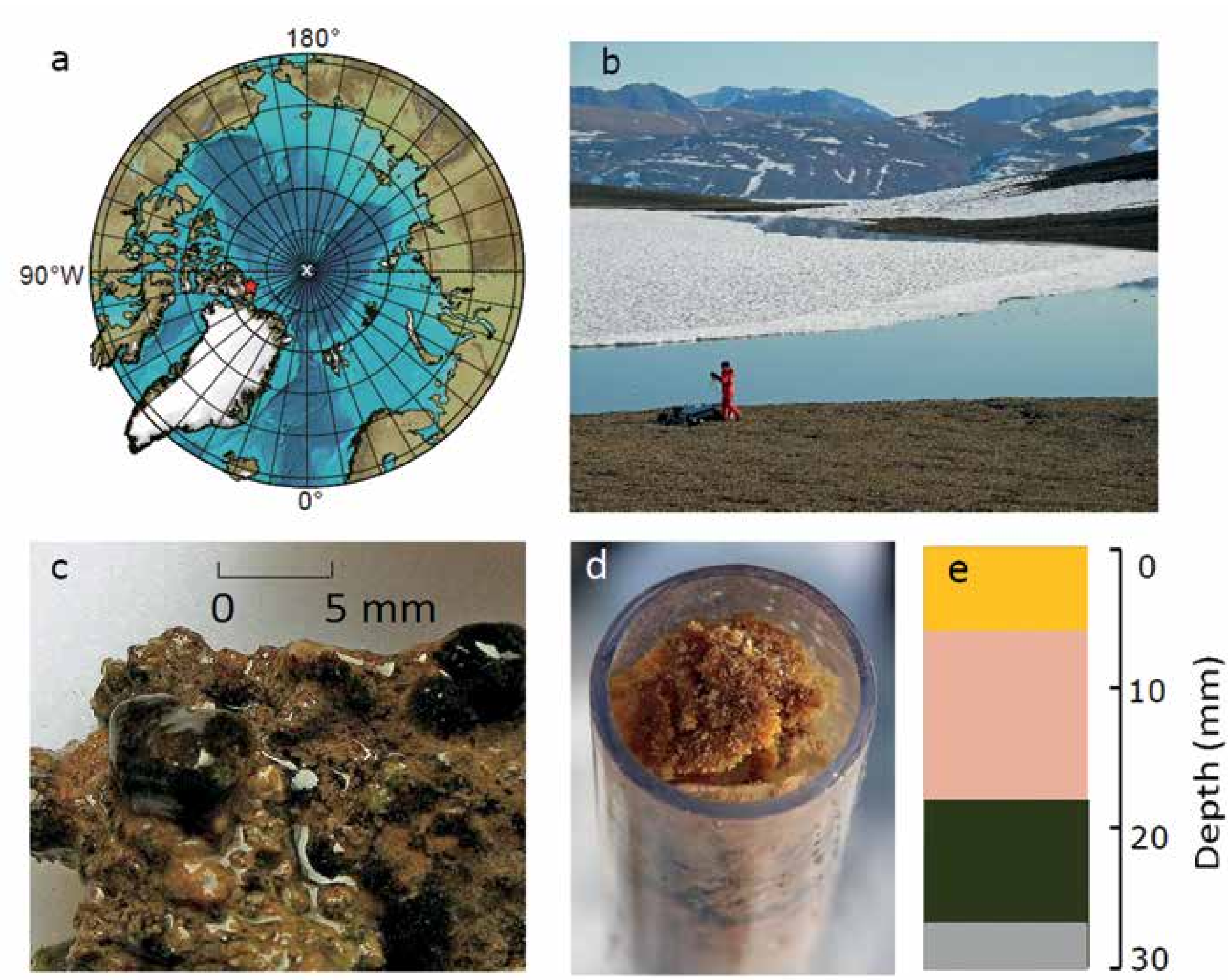

Figure 7. Molecular analysis of biofilms at Ward Hunt Lake (location: top left; western side of lake: top right) revealed striking differences between shallow water communities (bottom left) and deep water communities (bottom right). From Mohit et al. (2017). © Mohit, Culley, Lovejoy, Bouchard, Vincent 2017.

Milne Fjord

A major advance this year was the familiarization and successful use of the hole melter we brought to Milne Fiord. A 16” hole was drilled through 8.6 m of ice to reach the waters under the Milne Ice Shelf. The team deployed a sonar system through this hole to attempt to map in detail the morphology of the channel, and to investigate the seabed topography beneath the ice shelf. The team was able to drive their ROV, equipped with a GoPro, through the channel for 5-10 meters. This was very exciting as it is the first time we have seen what it looks like beneath an ice shelf in the Canadian Arctic; preliminary observations indicated a false floor or bench in the channel. This view of the channel refuted an earlier hypothesis that the ice shelf was grounded at this location (we were led to believe this in 2015 from short CTD casts that hit sediment). Ice penetrating radar data corroborated the explanation that there was a localized ‘bench’ in the wall of the channel. The epishelf lake depth was found to be approximately 7.5 m deep which indicates no major changes from the trend in lake shoaling. The seismometers did not record any identifiable ice quakes.

Iqaluit/Frobisher Bay

The team conducted 14 aerial surveys and took thousands of photos for processing (Figure 8). Martin St.Amant is currently working on determining SfM-generated topographic accuracy and precision. At this point, we are confident that sea ice topography can be measured easily and with little cost (relative to LIDAR) using UAV surveys and will continue to evaluate best practices for future surveys.

Baffin Bay

In spite of not being able to reach the ice island that she was to work on, we had a productive season. Jill Rajewicz was able to deploy several satellite tracking beacons on ice islands (Figures 9A, B) and assisted

Figure 8. Adam Garbo operating the uninhabited aerial vehicle (UAV) equipped with a camera and high-precision GPS on the sea ice in Frobisher Bay. Photo credit: M. St.Amant.

Luke Copland’s research group in deploying tracking beacons. The equipment that was on the ice island recorded approximately 6 m of melt in 2015-16.

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. We are continuing to develop Nordicana D as a bilingual, online, open-access doi-referenced data repository [see CEN (2018) for Northern Frontier climate data, for example], and this now houses important doi-referenced ArcticNet data sets, cross-referenced in Polar Data Catalogue, including a new compilation of organic carbon data for circumpolar freshwaters (Wauthy et al. 2017 with new matched PDC entry). Nordicana D data sets are now being cited in journals such as those published by the NRC Press (Arctic Science), the European Geophysical Union (The Cryosphere), the American Geophysical Union (JGR) and John Wiley & Sons Inc (multiple journals). Glacier mass balance data for White Glacier continues to be submitted annually to the World Glacier Monitoring Service, to continue the record first started in 1959.

Figure 9. Ice island research in 2017. A (above): Ice island fragment in Baffin Bay, with an approximate maximum width of 700 m and estimated freeboard of 20 m. A tracking beacon was deployed on the ice island for Environment and Climate Change Canada/Canadian Ice Service. B (below) Jill Rajewicz (Carleton University) and Abigail Dalton (University of Ottawa) make a measurement of ice thickness on an ice island fragment in North Baffin Bay (as seen in Figure 9A).

Outreach

We continue to be involved in many ArcticNet outreach activities. For example, the Amundsen and Northern Frontier team member Jill Rajewicz were profiled in the December issue of Owl Magazine, and we were interviewed by journalists for print (e.g. UA Affairs), radio (e.g.,CBC and Radio Canada), TV (e.g., Radio France) and online media (e.g., Arctic Deeply; PNAS Front Matter). We gave overview talks to a wide variety of audiences, including to Arctic Change participants, senior Federal policy makers and a Senate standing committee.

DISCUSSION

The Ward Hunt and Milne Fjord sites continue to provide valuable long term records at the northern coastline of Canada. 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.

Our work on aquatic microbial ecosystems is continuing to reveal new community structures and components, and by way of metagenomic analysis, has begun to provide insight into not only the taxonomic but also the functional diversity of these northern most communities.

We continue to advance 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.

Our 2017 research shows that the channel that drains the epishelf lake through/under the Milne Ice Shelf is dynamic and enigmatic. There is a unique opportunity to study ice-ocean processes before this vulnerable system changes dramatically. The epishelf lake continues to thin at approximately the same rate predicted by Hamilton et al. (2017). The changes in the last deep epishelf lake in the Northern Hemisphere are well monitored by the Milne Fiord mooring – the longest running oceanographic mooring in a Canadian Arctic fjord. We will repeat our seismographic observations at the grounding zone of the Milne Glacier with our South Korean collaborators. This summer, seismometers placed directly on the surface of the ice will provide increased sensitivity to motion. We are exploring new techniques to examine grounding line dynamics with the use of satellite interferometry and this will be supplemented with in situ ice-penetrating radar measurements.

Our new results indicate a strong connection between the timing of sea ice breakup adjacent to glaciers on Ellesmere Island, and the timing of iceberg calving events. Given rapid recent reductions in sea ice coverage in the Canadian Arctic, further work is required to understand whether this is resulting in a long-term increase in iceberg production from glaciers across the study region. Overall, surface mass balance continues to be strongly negative on glaciers and ice caps across northern Ellesmere and Axel Heiberg Islands, following a pattern that has intensified since the start of the 21st century. Ice motion measurements indicate a general slowdown of land-terminating glaciers in the Canadian Arctic over the past ~50 years, but a rapid acceleration of some tidewater-terminating glaciers over the past couple of decades. This highlights the importance of understanding the role of ice-ocean interactions in controlling the dynamics of Arctic glaciers.

Our sea ice topography results are still preliminary but the techniques that we are refining seem to have promise over other more expensive techniques. We have been interacting with other researchers, providing advice regarding instrument setup and UAV deployment in cold environments.

Our ice island deterioration record is the first of its kind in the Eastern Arctic. Anna Crawford is currently preparing a manuscript for publication that calibrates ice melt models using our data (with several ArcticNet and Green Edge co-authors). It will also be used to validate an ice island fracture model pending new field observations in the spring.

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 deep water sediments 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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REFERENCES

Antoniades, D. (2017) An overview of paleoenvironmental techniques for the reconstruction of Arctic ice shelves. In: Copland L, Mueller DR (eds) Arctic Ice Shelves and Ice Islands. Springer SBM, Dordrecht, in press.

Antoniades D, Francus, P, Pienitz R, St-Onge G and Vincent WF. 2011. Holocene dynamics of the Arctic's largest ice shelf. Proceedings of the National Academy of Sciences of the United States of America 108 (47), 18899-18904.

Bradley RS, Retelle MJ, Ludlam, SD Hardy, DR, Zolitschka B, Lamoureux SE and Douglas, MSV.1996. The Taconite Inlet Lakes Project: A systems approach to paleoclimatic reconstruction. Journal of Paleolimnology 16, 97-110.

CEN 2018. Climate station data from Northern Ellesmere Island in Nunavut, Canada, v. 1.5 (2002-2017). Nordicana D1, doi: 10.5885/44985SL-8F203FD3ACCD4138.

Copland L, Mueller DR and Weir L. 2007. Rapid loss of the Ayles Ice Shelf, Ellesmere Island, Canada. Geophysical Research Letters 34, L21501, doi:10.1029/2007GL031809.

Copland L., White, A., Crawford, A., Mueller, D.R. 2, Van Wychen, W. Thomson, L., Vincent W.F. 2017. Glaciers, Ice Shelves and Ice Islands. In Bell , T. (ed) Nunavut Integrated Regional Impact Study. ArcticNet Inc., Quebec City, Canada (in press).

England, JH, Lakeman, TR, Lemmen, DS, Bednarski, J, Stewart, TG and Evans, DJA. 2008. A millenial-scale record of Arctic Ocean sea ice variability and the vulnerability of the Ellesmere Island ice shelves. Geophysical Research Letters 35, L19502, doi:10.1029/2008GL034470.

Lafreniere, M., Lamoureux, S. F., Young, K. L., Vincent, W. F., Muir, D. C. G., and Kirk, J. L. 2017. Drivers, trends and uncertainties of changing freshwater systems in the Eastern Canadian Arctic. In Bell , T. (ed) Nunavut Integrated Regional Impact Study. ArcticNet Inc., Quebec City, Canada pp.(in press – follow up).

Lovejoy C, Comeau A, Thaler M 2016. Curated reference database of SSU rRNA for northern marine and freshwater communities of Archaea, Bacteria and microbial eukaryotes, v.1.1 (2002-2008).Nordicana D23, doi:10.5885/45409XD-79A199B76BCC4110.

Mohit, V., Culley, A., Lovejoy, C., Bouchard, F. and Vincent, W.F. 2017. Hidden biofilms in a far northern lake and implications for the changing Arctic. npj Biofilms and Microbiomes 3:17, doi:10.1038/s41522-017-0024-3.

Mortimer, C., Copland, L. and Mueller, D. 2012. Volume and area changes of the Milne Ice Shelf, Ellesmere Island, Nunavut, Canada, since 1950. Journal of Geophysical Research Earth Surface, 117, F04011.

Mueller DR, Vincent WF, Jeffries MO. 2003. Break-up of the largest Arctic ice shelf and associated loss of an epishelf lake. Geophysical Research Letters 30, 2031, doi:10.1029/2003GL017931.

Mueller DR, Copland L, Jeffries MO. 2017. Northern Ellesmere Island ice shelf and ice tongue extents, v. 1.0 (1906-2015). Nordicana D28, doi: 10.5885/45455XD-24C73A8A736446CC.

NEIGE 2016a. Phytoplankton pigments of lakes and fiords of Northern Ellesmere Island, Nunavut, Canada, v. 1.0. Nordicana D26, doi: 10.5885/45436CE-0E0A89CB98C148F4.

NEIGE 2016b. Water column physico-chemical profiles of lakes and fiords along the northern coastline of Ellesmere Island, v. 1.0. Nordicana D27, doi: 10.5885/45445CE-7B8194DB81754841.

Paquette M, Fortier D, Mueller DR, Sarrazin D ,Vincent W.F. 2015. Rapid disappearance of perennial ice on Canada's most northern lake. Geophysical Research Letters 42, 1433-1440, doi: 10.1002/2014GL062960.

Peterson, IK. 2005. Large tabular icebergs and ice islands off Eastern Canada in 2001-2003 and their probable source, in: Proceedings of the 18th International Conference on Port and Ocean Engineering Under Arctic Conditions. Presented at the 18th International Conference on Port and Ocean Engineering Under Arctic Conditions, Potsdam, USA, pp. 143-152.

Thomson L and Copland L. 2016. White Glacier 2014, Axel Heiberg Island, Nunavut; Mapped using structure from motion methods, Journal of Maps, doi: 10.1080/17445647.2015.1124057.

Tsuji, M., Tanabe, Y., Vincent, W.F., and Uchida, M. 2017a. *Gelidatrema psychrophila* sp. nov., a novel yeast species isolated from an ice island in the Canadian High Arctic. Mycoscience 59: 67-70, doi: 10.1016/j.myc.2017.08.010.

Tsuji, M., Tanabe, Y., Vincent, W.F., and Uchida, M. 2017b. *Mrakia arctica* sp. nov., a new psychrophilic yeast isolated from an ice island in the Canadian High Arctic. Mycoscience 59: 54-58.

Van Wychen, W., Davis, J., Burgess, D.O., Copland, L., Gray, L., Sharp, M. and Mortimer, C. 2016. Characterizing interannual variability of glacier dynamics and dynamic discharge (1999-2015) for the ice masses of Ellesmere and Axel Heiberg Islands, Nunavut, Canada. Journal of Geophysical Research Earth Surface, 121(1), 39-63.

Vincent WF, Whyte LG, Lovejoy C, Greer CW, Laurion I, Suttle CA, Corbeil J. 2009. Arctic microbial ecosystems and impacts of extreme warming during the International Polar Year. Polar Science 3 (3), 171-180, doi:110.1016/j.polar.2009.1005.1004.

Vincent WF, Fortier D, Levesque E, Boulanger-Lapointe N, Tremblay B, Sarrazin D, Antoniades D, Mueller DR. 2011. Extreme ecosystems and geosystems in the Canadian High Arctic: Ward Hunt Island and vicinity. Ecoscience 18 (3), 236-261, doi: 10.2980/18-3-3448.

Wauthy, M., Rautio, M., Christoffersen, K.S., Forsström, L., Laurion I., Mariash, H., Peura, S., Vincent, W.F. 2017. Dissolved organic carbon and related environmental data from ponds and lakes in the circumpolar North, v. 1.0 (2002-2016). Nordicana D31, doi: 10.5885/45520CE-0A48ADE0E2194290.

White A, Copland L, Mueller D, Van Wychen W. 2015. Assessment of historical changes (1959–2012) and the causes of recent break-ups of the Petersen ice shelf, Nunavut, Canada. Annals of Glaciology 56 (69), 65-76, doi:10.3189/2015AoG69A687.

PUBLICATIONS

Antoniades D. 2017. An overview of paleoenvironmental techniques for the reconstruction of past Arctic ice shelf dynamics. pp.207-226.

Barnard C., Cournoyer L., Vincent W.F., Sarrazin D, Elger K. Arctic Data Archiving and Dissemination: Development of the Environmental Data Repository Nordicana D. Arctic Change 14 December, 2017.

Bégin P. N., Rautio M., Vincent W.F. Littoral zones in High Arctic lakes and the implications of ice cover loss. Arctic Change, Québec City, 12 December 2017.

Bégin P.N., Vincent,W.F. 2017. Permafrost thaw ponds as habitats for abundant rotifer populations. Arctic Science 3: 354-377.

Belke Brea M., Barrère M., Domine F., G. Picard G, Arnaud, L. 2017 Shrub-induced modification of the grain size of the surface snow layer in fall and the resulting impact on albedo. Arctic Change 2017, Quebec City.

Berteaux D., Gauthier G., Domine F., Ims R.A., Lamoureux S.F., Lévesque E., Nigel Yoccoz N. 2017. Effects of changing permafrost and snow conditions on

tundra wildlife: critical places and times. Arctic Science 3: 65-90.

Bouchard F., Proult V., Pienitz R., Antoniades D., Tremblay R., Vincent W.F. 2018. Periphytic diatom community structure in thermokarst ecosystems of Nunavik (Quebec, Canada). Arctic Science 4, in press.

Comte J., Culley A., Lovejoy C., Vincent W.F. 2018. Microbiome connectivity and sorting in a High Arctic watershed. The ISME Journal. Under revision.

Copland L., Mortimer, C.A., White, A., Richer-McCallum, M., Mueller, D. The causes of calving events from Arctic ice shelves. In: Copland, L. and Mueller, D. (eds) Arctic Ice Shelves and Ice Islands, Springer Polar Sciences, Springer, Dordrecht, pp 263–285. doi:10.1007/978-94-024-1101-0_10.

Copland L., White, A., Crawford, A., Mueller, D.R., Van Wychen, W. Thomson, L., Vincent W.F. 2018. Glaciers, Ice Shelves and Ice Islands. In Bell, T. (ed) Nunavut Integrated Regional Impact Study. ArcticNet Inc., Quebec City, Canada pp. (in press).

Copland, L. 2018. A consistent estimate of pan-Arctic glacier frontal ablation, 2000-2015. Workshop on the Dynamics and Mass Budget of Arctic Glaciers, Obergurgl, Austria. Invited keynote talk.

Copland, L. and Mueller, D.R. (eds.), Arctic Ice Shelves and Ice Islands. Springer-Verlag, N.Y., 425 pp.

Copland, L., Dawson, J., Dalton, A. and Delaney, F. 2017. Iceberg Drift Tracking and Climatology of AIRSS (Arctic Ice Regime Shipping System) Indices. Report to Canadian Ice Service, Ottawa. 30 pp.

Copland, L., Herdes, E., Schaffer, N., Thomson, L. 2017. Long-term and short-term evolution of glacier velocities in northern Canada. International Glaciological Society Conference on the Cryosphere in a Changing Climate, Wellington, New Zealand.

Copland, L., Thomson, L. 2017. Changes in velocity of White Glacier, Axel Heiberg Island, Canada, over the past 50 years. Workshop on the Dynamics and Mass Budget of Arctic Glaciers, Bethel, Maine.

Copland, L., White, A., Van Wychen, W., Thomson, L., Mueller, D., Vincent, W.F., Hamilton, AK., Dalton, A., and Medrzycka, D. (2017) Rapid recent changes to glacial environments in the Canadian High Arctic. Arctic Change 2017, Quebec City, Quebec, December 11 - 15, 2017 (Oral).

Copland, L., White, A., Van Wychen, W., Thomson, L., Mueller, D., Vincent, W.F., Hamilton, A., Dalton, A., Medrzycka, D. 2017. Rapid recent changes to glacial environments in the Canadian High Arctic. Arctic Change 2017, Québec City, Canada.

Crawford A, Mueller D, Joyal G (Submitted) Surveying drifting ice islands and icebergs: deterioration detection, mass estimation and technique evaluation. Remote Sensing.

Crawford, A., Mueller, D., Joyal, G., and Crocker, G. (2017) High-precision surveying of drifting icebergs and ice islands. Ottawa-Carleton Student Northern Research Symposium. Carleton University, Ottawa, Ontario, March 10, 2017 (Poster).

Crevecoeur S., Vincent W.F., Comte J., Matveev A. Lovejoy C. 2017. Diversity and potential activity of methanotrophs in high methane-emitting permafrost thaw ponds. PLoS ONE 12: e0188223.

Cruaud P, Vigneron A, Fradette M, Charette SJ, Rodriguez MJ, Dorea C, Culley A. 2017. Open the Sterivex casing: an easy and effective way to improve DNA extraction yields. Limnology and Oceanography: Methods. 15: 1015-1020.

Culley A. 2018. New insight into the RNA aquatic virosphere via viromics. Virus Research. 244:84-89.

Dalton, A. and Copland, L. 2017. Tracking changes in iceberg calving events and characteristics from Trinity and Wykeham Glaciers, SE Ellesmere Island, Canada. 2017 Eastern Snow Conference, Ottawa, Canada.

Déraspe M, Raymond F, Boisvert S, Culley A, Roy P, Laviolette F, Corbeil J. 2017. Phenetic comparison of genomes using k-mers for evolutionary analysis of prokaryotes. Molecular Biology and Evolution. doi:10.1093/molbev/msx200.

Deshpande B.N., Maps F., Matveev A., Vincent W.F. 2017. Oxygen depletion in subarctic peatland thaw lakes. Arctic Science 3: 406-428.

Domine F., Barrère M., Belke-Brea M., Sarrazin D. 2017. Snow-climate-vegetation-permafrost feedbacks and the prediction of permafrost thaw. Arctic Change 2017, Quebec City.

Grosbois G, Mariash H, Schneider T, Rautio M. 2017. Under-ice availability of phytoplankton lipids is key to freshwater zooplankton winter survival. Scientific Reports 7: 11543.

Hamilton A.K., Laval B.E., Mueller D.R., Vincent W.F., Copland L. 2018. Dynamic response of an Arctic epishelf lake to seasonal and long-term forcing: implications for ice shelf thickness. The Cryosphere 11: 2189–2211.

Hamilton AK, Mueller D, Laval BE. (In revision) Ocean properties and variability in an ice shelf-dominated High Arctic glacial fjord. Journal of Geophysical Research - Oceans.

Hamilton, A., Mueller, D., Laval, B.E. and Copland, L. (2017) Modification and variability of ocean properties in a High Arctic ice shelf fjord: Milne Fiord, Ellesmere Island. Arctic Change 2017, Quebec City, Quebec, December 11 - 15, 2017 (Oral).

Jungblut A., Raymond F., Mohit V., Culley A., Lovejoy C., Corbeil J., Vincent, W.F. From Captain Nares's British Arctic Expedition (1875-76) to the present: Application of genomics to identify historical and modern microbiomes as sentinels of Arctic change. Arctic Change, Quebec City, 14 December 2017.

Jungblut A.D., Mueller D.R., Vincent W.F. 2017. Arctic ice shelf ecosystems. In: Copland, L. and Mueller, D.R. (eds.), Arctic Ice Shelves and Ice Islands. Springer-Verlag, N.Y. pp 227-260.

Jungblut A.D., Vincent, W.F. 2017. Cyanobacteria in polar and alpine ecosystems. In: Margesin, R. (ed.) Psychrophiles: From Biodiversity to Biotechnology. Springer, Heidelberg, pp. 181-206.

Kleinteich J., Hildebrand F., Bahram M., Voigt A Y., Wood S. A., Jungblut A. D., Küpper F. C., Quesada A., Camacho A., Pearce D. A., Convey P., Vincent W. F., Zarfl C., Bork P., Dietrich D. R. 2017. Pole-to-pole connections: Similarities between Arctic and Antarctic microbiomes and their vulnerability to environmental change. Frontiers in Ecology and Evolution, 5: 137.

Labbé M, Vincent WF, Culley A. Diversité et dynamiques des virus aquatiques du Haut Arctique Canadien. dans un contexte de changements climatiques. Première réunion annuelle de Sentinelle Nord. Québec, QC. 30/08/2017.

Labbé M, Vincent WF, Culley A. Diversité et dynamiques des virus aquatiques du Haut Arctique Canadien. Rencontre printanière du Centre d'études nordiques. La Pocatiere QC. 04/05/2017.

Lafreniere, M., Lamoureux, S. F., Young, K. L., Vincent, W. F., Muir, D. C. G., Kirk, J. L. 2018. Drivers, trends and uncertainties of changing freshwater systems in the Eastern Canadian Arctic. In Bell, T. (ed) Nunavut Integrated Regional Impact Study. ArcticNet Inc., Quebec City, Canada. (in press).

Levésque A, Marois C, Labrie S, Vincent A, Moineau S, Vincent WF, Culley A. Isolation and characterization of two novel cyanhophages from a subarctic Canadian Lake. 22nd Biennial Evergreen International Phage Meeting. Olympia, WA. 6/8-11/8/2017.

Mariash HL, Cazzanelli M, Rautio M, Hamerlik L, Wooller MJ, Christoffersen KS. 2018. Changes in food web dynamics of low arctic ponds with varying content of dissolved organic carbon. Arctic, Antarctic, and Alpine Research.

Marois C, Culley A. Dynamique hôte-cyanophage provenant du subarctique. Journée des stagiaires. Groupe de recherche en écologie buccale/ Faculté de médecine dentaire. Québec, QC. 7/7/2017.

Matveev, A., Laurion, I., Vincent, W.F. 2018. Greenhouse gas emissions from thermokarst lakes on mineral soils. Arctic Science 4: in revision.

Mohit V., Culley A., Bouchard F., Lovejoy C., Vincent W.F. 2017. Hidden biofilms in a far northern lake and implications for the changing Arctic. npj Biofilms and Microbiomes 3:17.

Mueller, D., Copland, L., Jeffries, M.O. 2017. Changes in Canadian Arctic ice shelf extent since 1906. In: Copland, L. and Mueller, D. (eds.) Arctic Ice Shelves and Ice Islands, Springer Polar Sciences, Springer, Dordrecht, pp 109-148. doi:10.1007/978-94-024-1101-0_5.

Paquette M., Fortier D., Vincent W.F. 2017. Water tracks in the High Arctic: A hydrological network dominated by rapid subsurface flow through patterned ground. Arctic Science 3: 334-353.

Paquette, M., Fortier, D., Vincent, W.F. 2018. Hillslope water tracks in the High Arctic: Seasonal effects of water sources on flow pathways. Hydrological Processes, in revision.

Pimentel, S., Flowers, G.E., Sharp, M.J., Danielson, B., Copland, L., Van Wychen, W., Duncan, A. and Kavanaugh, J. 2017. Modelling intra-annual dynamics of a major marine-terminating Arctic glacier. Annals of Glaciology, doi: 10.1017/aog.2017.23.

Pope, S., Copland, L., and Alt, B. 2017. Recent changes in sea ice plugs along the northern Canadian Arctic Archipelago. In: Copland, L. and Mueller, D. (eds.). Arctic Ice Shelves and Ice Islands. Springer Nature, Dordrecht.

Przytulska, A., Bartiowicz, M. Vincent, W.F. 2017. Increased risk of harmful cyanobacterial blooms in northern high-latitude lakes through climate warming and phosphorus enrichment. Freshwater Biology 62: 1986-1996.

Rajewicz, J., Mueller, D. (2017) Channelized freshwater drainage beneath Milne Ice Shelf, Ellesmere Island, Nunavut. Arctic Change 2017, Quebec City, Quebec, December 11 - 15, 2017 (Oral).

Saper, R. and Mueller, D. (2017) Iceberg monitoring using synthetic aperture radar: A technology roadmap and research gaps. CAGONT 2017, Kingston, Ontario, October 20-21, 2017 (Oral).

Saper, R. and Mueller, D. (2017) On iceberg severity count distribution and implications of exceptionality of iceberg survival for modelling approaches. Ottawa-Carleton Student Northern Research Symposium. Carleton University, Ottawa, Ontario, March 10, 2017 (Oral).

Sazidy, M., Crocker, G., Mueller, D., and Smith, J. (2017) A computationally efficient finite element model to simulate large scale fracture in ice island. Arctic Change 2017, Quebec City, Quebec, December 11 - 15, 2017 (Oral).

Schaffer, N., Copland, L. and Zdanowicz, C. 2017. Ice velocity changes on Penny Ice Cap, Baffin Island, since the 1950s. Journal of Glaciology, 63(240), 716-730.

Schneider T., Grosbois, G., Vincent, W.F., Rautio, M. 2017. Saving for the future: Pre-winter uptake of algal lipids supports copepod egg production in spring. Freshwater Biology 62: 1063-1072.

Thaler, M., Vincent, W.F., Lionard, M., Hamilton, A.K., Lovejoy, C. 2017. Microbial community structure and interannual change in the last epishelf lake ecosystem in the North Polar Region. Frontiers in Marine Science 3:275.

Thomson, L. and Copland, L. 2017. Multi-decadal reduction in glacier velocities and mechanisms driving deceleration at polythermal White Glacier, Arctic Canada. Journal of Glaciology, 63(239), 450-463.

Thomson, L. and Copland, L. In press. Changing contribution of peak velocity events to annual velocities following a multi-decadal slowdown at White Glacier. Annals of Glaciology.

Thomson, L., Copland, L. 2017. Changing contribution of short-term velocity events to annual velocities following a multi-decadal slowdown at White Glacier. International Glaciological Society Conference on The Cryosphere in a Changing Climate, Wellington, New Zealand.

Thomson, L., Copland, L. 2017. Multi-decadal response and stability of White Glacier, Nunavut. 2017 Eastern Snow Conference, Ottawa, Canada.

Thomson, L., Flowers, G., Copland, L. 2017. Englacial temperature changes in a high-Arctic polythermal glacier: 1960-2017. Arctic Change 2017, Québec City, Canada.

Thomson, L., Zemp, M., Copland, L., Cogley, G. and Ecclestone, M. 2017. Comparison of geodetic and glaciological mass budgets: White Glacier, Axel Heiberg Island, Canada. Journal of Glaciology, 63(237), 55-66.

Tsuji M., Tanabe Y., Vincent W.F., Uchida M. 2017. Mrakia arctica sp. nov., a new psychrophilic yeast isolated from an ice island in the Canadian High Arctic. Mycoscience 59: 54-58.

Tsuji M., Tanabe Y., Vincent W.F., Uchida, M. 2017. Gelidatrema psychrophila sp. nov., a novel yeast species isolated from an ice island in the Canadian High Arctic. Mycoscience 59: 67-70.

Van Wychen, W., Davis, J., Copland, L., Burgess, D.O., Gray, L., Sharp, M., Dowdeswell, J. and Benham, T. 2017. Variability in ice motion and dynamic discharge from Devon Ice Cap, Nunavut, Canada. Journal of Glaciology, 63(239), 436-449.

VanWychen, W. and Copland, L. 2017. Ice island drift mechanisms in the Canadian High Arctic. In: Copland, L. and Mueller, D. (eds.). Arctic Ice Shelves and Ice Islands. Springer Nature, Dordrecht.

Vigneron A., Lovejoy C., Culley A., Vincent W. F. Microbiomes arctiques: potentielles sentinelles des changements climatiques". l'AFEM, 17-20 Octobre 2017, Camaret-sur-Mer, France.

Vincent W.F., Allard M., Lemay M. Arctic Development and Adaptation to Permafrost in Transition: ADAPT Perspectives on Permafrost Systems. Arctic Change, Quebec City, 13 December 2017.

Vincent W.F., Lemay M., Allard M. 2017. Arctic permafrost landscapes in transition: Towards an integrated Earth system approach. Arctic Science 3: 39-64.

Vincent, W.F. 2018. Lakes – A Very Short Introduction. Oxford University Press, Oxford, U.K., 168 pp.

Wauthy, M., Rautio, M., Christoffersen, K. S., Forsström. L., Laurion, I., Mariash, H., Peura, S., Vincent, W.F. 2018. Increasing dominance of terrigenous organic matter in circumpolar freshwaters due to permafrost thaw. Limnology and Oceanography Letters, 2: in press.

Wolken, G., Sharp, Andreassen, L., Burgess, D., Copland, L., Kohler, J., O'Neel, S., Pelto, M., Thomson, L. and Wouters, B. 2017. Glaciers and ice caps outside Greenland. In: Blunden, J. and Arndt, D.S. (eds.). State of the Climate in 2016. Bulletin of the American Meteorological Society¸ 98(8), S140-S143.

SECTION III. INUIT HEALTH, EDUCATION AND ADAPTATION

Section III is composed of four ArcticNet research projects covering many components of human health and education under adaptation perspectives of climate change and modernization.

DESIGNING AND IMPLEMENTING THE NUNAVIK HEALTH SURVEY *QANUIPPITAA* 2016

Project Team

Pierre Ayotte (Project Leader), Richard Bélanger, Suzanne Côté, Aimée Dawson, Véronique Doutreloux, Julie Ducrocq, Christopher Fletcher, Christopher Furgal, Élizabeth Gagné, Chantal Galarneau, Judith Labrecque, Jacinthe Larochelle, Mélanie Lemire, Alexandre Léveillé, Benoit Lévesque, Michel Lucas, Marie-Claude Lyonnais, Caroline Moisan, Gina Muckle, Nathalie Ouellet, Natalia Poliakova, Michel Poulin, Mylène Riva

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.
- Additional funding for *Qanuilirpitaa?* was obtained from the Northern Contaminants Program (Indigenous and Northern Affairs Canada).

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 a 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

Communications of results to participants and local health clinics

- Letters informing participants and local health clinics of the main results (clinical tests and laboratory analyses) will be sent in June 2017. Results requiring immediate action were rapidly sent to the health clinics and follow-up was monitored.

Reports and publications

- We are preparing jointly with INSPQ and the NRBHSS a descriptive report that will include results of themes identified as priorities by the region. This report will serve 1) to support building a new regional hospital; 2) to identify new strategies for improving health and well-being of Nunavimmiut; and 3) to support the clinical projects in Nunavik.

- A Nunavik Health portrait is also being prepared that targets a wider audience (general public, regional organisations, etc.).
- Thematic reports will then be prepared, followed by research publications.
- Interactive community assets maps will be prepared and made available to communities and the Nunavik region. Furthermore, community and regional health portraits will be produced.

Presentations to conferences

- Ayotte, P. Qanuilirpitaa 2017: l'enquête de santé chez les Inuit du Nunavik. Journée de la science de l'INQ, Musée de la civilisation, 6 juin 2017, Québec, QC.
- Ayotte P. Bilan de 25 ans de recherche sur l'exposition aux contaminants environnementaux chez les Inuits du Nunavik. Conférencier invité - LCABIE, Université de Pau et des Pays de l'Adour, 29 septembre 2017, Pau, France.
- Ayotte P. Enquête de santé auprès des Inuits du Nunavik: Comment allons-nous maintenant? Forum science environnement, MDDELCC, 8 novembre 2017, Québec, QC.
- Ayotte P, Bouchard F, Grey M, St-Laurent D. *Qanuilirpitaa?* 2017 The Nunavik Inuit Health Survey. International Arctic Change Conference, December 11-15 2017, Québec, QC.
- Riva M, Lynch M, Fletcher C. Integrating Inuit community perspectives in the "Community Component" of the *Qanuilirpitaa?* 2017 Nunavik Health Survey, International Arctic Change Conference, December 11-15 2017, Québec, QC.
- Moisan C, Jeannie C, Shipaluk L, Muckle G, Bélanger RE. Understanding attitudes toward early pregnancy among women in Nunavik: a qualitative study. International Arctic Change Conference, December 11-15 2017, Québec, QC.
- Riva M, Baron M, Fletcher C. Conceptualisation and operationalisation of a holistic indicator of health for aging Inuit. International Arctic Change Conference, December 11-15 2017, Québec, QC.

INTRODUCTION

The responsibilities of the Nunavik Regional Board of Health and Social Services (NRBHSS) in the areas of information on, and monitoring of, Nunavimmiut's health are defined according to two contexts: the NRBHSS's mission itself and the legal mandate of the regional public health director (*Act Respecting Health and Social Services*, sections 371-375).

Within this framework, only two regional health surveys undertaken in Nunavik were conducted: the 1992 Inuit Health Survey and *Qanuippitaa* 2004. Since then, no other survey allowing for an update of the information on the health of this population has been conducted. Further, it is extremely difficult and expensive, indeed impossible, to extend existing Quebec surveys to this region to obtain this information, for multiple reasons: language and cultural barriers, methodological considerations, the need to adapt tools, administrative and transportation costs, the need to carry out the related work on site (since the data-gathering methods used in Quebec are not applicable), and so forth.

One of the lasting benefits of the *Qanuippitaa?* 2004 survey has been the working relationship between the Population Health Unit at the CHU de Quebec Research Centre, the Institut national de santé publique du Québec (INSPQ) and the NRBHSS. This relationship provides a solid base for the development of a follow-up to the 2004 health survey.

Several reasons and preoccupations justify this initiative:

- Recognition of new priorities: youth health, tuberculosis, food insecurity, mental health, suicide, addictions, violence and others;

- Upcoming development of the Plan Nord, which 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;
- Current clinical projects whose objectives are to implement preventive strategies and services in close partnership with the communities and with concern for strengthening community capacities and fostering empowerment;
- The need to obtain data required to support the next Strategic Regional Plan for health and social services (starting in 2016).

Thus, in February 2014, the NRBHSS board of directors (composed of representatives of the region's 14 communities and the two health centres) unanimously adopted a resolution to conduct a new health survey in Nunavik.

In 2013 and 2014, Nunavik regional organizations conducted a vast consultation in all communities, Parnasimautik, to identify preoccupations and issues among Nunavimmiut. Their report provides further impetus for conducting a new health survey to better document health and social issues with a view to supporting actions that target health and its social and environmental determinants in Nunavik. While continuity between the new survey and the previous ones is necessary in order to assess the evolution of certain trends, the new survey must also move beyond traditional survey approaches and comply with contemporary paradigms for developing knowledge in Nunavik, in order to properly reflect the characteristics of the population and its communities.

For Nunavimmiut, health depends on the balance and harmony of economic, cultural, environmental and biological factors. It is thus reflected through individual level attributes (e.g., diseases, limitations, lifestyles) and broader societal and cultural factors (e.g., social supports, community wellness, social policies and programs, traditions). The involvement of key regional partners is thus important in order to provide the necessary links to factors that can influence the health of Nunavimmiut and their community.

ACTIVITIES

From August 19 to October 5 2017, a total of 1326 Nunavimmiut were recruited and visited the *Amundsen* for a 2 ½ hour period that involved anthropometric measurements, collection of various biological samples, questionnaires and clinical tests (spirometry, dental examination). The number of participants recruited are listed in Table 1 according to age, sex and community of residence. The number of participants who were part of the 2004 Survey is also indicated.

RESULTS AND DISCUSSION

We had initially envisioned recruiting approximately 2000 participants. After the first few days of the survey, in order to obtain quality data, we had to reduce our targeted number of participants to 1674. We ended up recruiting 1326 participants, corresponding to 79.2% of our revised target number. Bad weather and a rescue mission in Iqaluit resulted in several clinic days being lost.

Biological samples were sent to laboratories for analyses. Most results were received and letters to partipicants and local CLSC are being prepared and will be sent in June 2018.

Eight databases are being prepared to produce the different outputs of the project. These are: 1) Questionnaires; 2) Laboratory tests; 3) Lung function (spirometry); 4) Dental examination; 5) Clinical measurements; 6) Auxiliary data; 7) Body composition data; 8) Medical file review data.

Table. 1 Participants recruited in the Qanuilirpitaa? Survey by community of residence, age categories and sex.

Community		16-30			31 +						Total		
		Female	Male	Total	Female		Male		Total		Female	Male	Total
					All	Cohort 2004	All	Cohort 2004	All	Cohort 2004			
Hudson	Akulivik	21	17	38	16	10	11	6	27	16	37	28	65
	Inukjuak	54	28	82	64	29	31	12	95	41	118	59	177
	Ivujivik	9	0	9	12	6	6	5	18	11	21	6	27
	Kuujjuarapik	10	10	20	24	8	17	3	41	11	34	27	61
	Puvirnituq	45	20	65	34	17	23	12	57	29	79	43	122
	Salluit	48	22	70	53	26	28	9	81	35	101	50	151
	Umiujaq	13	4	17	17	2	17	5	34	7	30	21	51
	Total	**200**	**101**	**301**	**220**	**98**	**133**	**52**	**353**	**150**	**420**	**234**	**654**
Ungava	Aupaluk	14	5	19	18	6	7	2	25	8	32	12	44
	Kangiqsualujjuaq	40	19	59	66	25	35	15	101	40	106	54	160
	Kangiqsujuaq	24	7	31	28	13	21	10	49	23	52	28	80
	Kangirsuk	11	13	24	19	10	21	8	40	18	30	34	64
	Kuujjuaq	65	17	82	93	38	39	14	132	52	158	56	214
	Quaqtaq	18	5	23	15	3	8	3	23	6	34	13	47
	Tasiujaq	22	13	35	20	3	9	5	29	8	42	22	64
	Total	**194**	**79**	**273**	**259**	**98**	**140**	**57**	**399**	**155**	**454**	**219**	**673**
Nunavik		**394**	**180**	**574**	**479**	**196**	**273**	**109**	**752**	**305**	**873**	**453**	**1326**

More specifically:

- From August 19 to October 5 2017, a total of 752 Nunavimmiut aged 31 years and over participated to the survey, including 305 participants from the 2004 survey. Several themes in physical health and mental health were covered;
- A total of 575 Nunavimmiut aged 16 to 30 years were recruited. The main focus of this component was mental health (Table 1); and
- Participants answered questions related to community health in individual questionnaires. In addition, semi-directed interviews were conducted with key individuals to identify community assets. Furthermore community asset mapping was conducted.

CONCLUSION AND ACKNOWLEDGEMENTS

This survey will allow to:

- Provide an overall population health profile to support healthy community development;
- Provide a baseline assessment of health and social conditions in Nunavik communities that may be affected by forthcoming economic and resource development in the region (Plan Nord);
- Assess adult health status in 2017 and follow up on the health and determinants of adult participants since 2004;
- Assess the health status of Nunavik youth;
- Assess the intergenerational evolution of health and its determinants in the age group 18-30 of 2017 as compared to the same age group of 2004;
- Improve our understanding of health and social issues;
- Provide essential information to support the next Strategic Regional Plan of the health and social services sector;
- Nurture the research competencies and skills of Inuit;
- Help in specifying further areas for future research.

Data analyses will follow to produce the different reports requested by the region and then scientific articles. Thanks to the close collaboration with Inuit organisations and adoption of a strong participatory approach, the data collection phase of the *Qanuilirpitaa?* Survey was completed with success. Data analysis and interpretation are underway.

COMMUNITY VULNERABILITY, RESILIENCE AND ADAPTATION TO CLIMATE CHANGE IN THE CANADIAN ARCTIC

Project Team

James Ford (Project Leader), Darya Andersen, Dylan Clark, Ashlee Cunsolo, Nathan Debortoli, Frank Duerden, David Fawcett, William Gough, Sherilee Harper, Eric Lede, Tristan Pearce, Jesse Sayles

ABSTRACT

The overarching goal of this research program is to develop a dynamic understanding of the processes and conditions affecting community vulnerability, resilience and adaptation to climate change. The program will build on completed vulnerability, resilience and adaptation research to develop and validate a novel, longitudinal community-based monitoring approach. This includes: (1) longitudinal reanalysis: replicate community vulnerability assessments conducted ten years prior to examine how continuing socio-ecological changes have affected human-environment interactions. Data will be collected using semi-structured interviews, focus groups, and participant observation; and (2) community-based monitoring: equip Inuit hunters with GPS units to take on every trip throughout the year to record land use data, followed with a series of fixed questions on their activities. Questions will focus on decisions made, hazards faced, coping mechanisms used, unusual conditions encountered, challenges experienced, and changes observed. Such monitoring will help develop real-time data on land-use, climate-related risks, adaptive responses, and limits to adaptation. The expected outcomes of this project will contribute to a dynamic understanding of how Inuit are affected by and respond to climate change, and identify opportunities to support Inuit adaptation.

KEY MESSAGES

- The main drivers of climate vulnerability are non-climatic, including weakening of land skills among younger generations, challenges associated with high food and housing insecurity, and colonial legacies.
- Communities are adapting to climate change autonomously. Some of these adaptations may increase vulnerability in the long-term.
- Indigenous knowledge systems underpin adaptability to change, and are evolving in-light of rapid climate change and emergence of new risks. It is unclear how such knowledge systems will evolve in the future to manage risk.
- New technology (e.g. unmanned aerial vehicles) offer opportunities for adaptation, but will have limited impacts unless underlying drivers of vulnerability are addressed.

RESEARCH 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 has developed a longitudinal community-based monitoring approach to achieve this, involving conducting re-studies of work conducted over a decade ago in partner communities to see how vulnerability has evolved, and intensively monitoring human-environment interactions over the duration of the project. The project is working in six communities across the Inuit Nunangat, and has a targeted focus on wildlife management & utilization, and dangers of engaging in land based activities. There are five specific objectives:

1. Develop a conceptual approach for capturing the dynamic nature of vulnerability and resilience in Arctic communities.
2. Develop and validate a novel, longitudinal community-based monitoring approach to identify and characterize the determinants of community vulnerability and resilience, and how they evolve over time.
3. Collect and analyze data on vulnerability and resilience in partner communities.
4. Use findings to inform adaptation planning initiatives in partner communities and regions.
5. Examine broader insights of the work both within the context of what the results illustrate for vulnerability and resilience in Inuit Nunangat, and more broadly for studies seeking to understand how climate change interacts with human systems.

KNOWLEDGE MOBILIZATION

Science assessments

- Lead authorship on IRIS 2 food security chapter & travelling and hunting chapter (Ford, Pearce).
- Lead authorship on Arctic Council's Adaptation Actions for a Changing Arctic assessment (chp. 11 &12) (Ford: 2015-2017).

Conference Presentations

- Ford, J. (forthcoming). Climate change vulnerability and Indigenous peoples in the Arctic. British Antarctic Survey workshop at the Royal Geographical Society, April 2018.
- Ford, J. (2018). Lessons from the Canadian Arctic on Adapting to Climate Change. Joint UK-Russia workshop on Arctic research, Scott Polar Research Institute, Cambridge University, January 12th.
- Ford, J., and Harper, S. (2017). Climate change adaptation in the Arctic. Enhancing resilience in

the face of global change. Mobilizing local and indigenous knowledge, UNESCO, Paris, October 2017. Plenary presentation and break-out session facilitator.

- Clark, D. Arctic Change (2017). Constraints and opportunities for Arctic search and rescue prevention and response.
- Clark, D. Arctic Change (2017). Mapping transportation system vulnerabilities to climate change across the Canadian Arctic.
- Clark, D. Northern Circumpolar Health Conference (2017). Search and Rescue in Nunavut.
- Flynn, M. Arctic Change (2017). Key principles and challenges for effective knowledge mobilization with Arctic communities.
- Galappaththi, E. Arctic Change (2017). How do Inuit fishers experience and respond to climate change? Empirical evidence from the Pangnirtung community in Nunavut, Canada.
- Anderson, D. Arctic Change (2017). Bakeapple picking in a changing physical and social landscape.
- Lede, E. Arctic Change (2017). We don't adapt in a vacuum: the role of multiple stressors in adaptation to climate change in Paulatuk, NT.
- Fawcett, D. Arctic Change (2017). Inuit adaptability to changing environmental conditions over an 11-year period: A case study of Ulukhaktok, NT.
- Flynn, M & J, Middleton. IK-ADAPT Gathering. (September 2017). Participatory methods: using seasonal calendars to explore our Arctic fieldwork experiences. Guelph, Canada.
- Flynn, M. IK-ADAPT Gathering. (September 2017). Key principles and challenges for effective knowledge mobilization with Arctic communities. Guelph, Canada.
- Pearce, T., Lede, E., van der Velden, M., Rietberg, D. (November, 2017). Building bridges between local & indigenous knowledge holders, scientists and policy-makers. Panel, UNESCO Pavilion, United Nations Climate Change Conference COP23, Bonn, Germany.
- Pearce, T., McTavish, K., O'Hara, S., Pamak, C., Watt, R., Illasiak, J., and Remmer, C. (2017). Conversation from the couch – community-based research in the Arctic. Panel discussion at Arctic Change, Quebec City, Canada, 11 December 2017.
- Pearce T (facilitator), Nakimayak, H., Huntington, H., Aragutak, A., and Pope, A. (2017). Visions of a future arctic. Panel discussion with at Arctic Change, Quebec City, 11 December 2017.

Community Workshops/ Dissemination Events

- Dylan led a UAV flying workshop in Arviat, Nunavut for youth involved in the Arviat Film Society. About 10 students participated and flew drones around the high school gym.Eranga led an art workshop in Pangnirtung Nunavut that focused on exploring youth experiences with boating and being on the land.
- Fawcett, D., Pearce, T. (2017). Hunting under changing conditions in Ulukhaktok: Climate change impacts on Inuit subsistence activities over an 11-year period. Website. https://tristanpearce.wixsite.com/ulukhaktok-lva.
- Fawcett, D., Pearce, T. (2017). The human face of climate change in the Inuvialuit Settlement Region. Oral presentation, Inuvialuit Settlement Region Research Day, Whitehorse, YK.
- Fawcett, D., Pearce, T. (2018). Hunting under changing conditions in Ulukhaktok: Climate change impacts on Inuit subsistence activities over an 11-year period. Dissemination booklet.
- Lalonde, G. (2018). Aspects of Inuit culture and modes of learning that should be included in education. Dissemination booklet.

- Lede, E., Pearce, T., Furgal, C. (2017). Adapting to Climate Change in Paulatuk – A Case Study on the Role of Multiple Stressors. Dissemination booklet.
- Lede, E. (2018). Adapting to Climate Change in Paulatuk – Key messages for the Hamlet of Paulatuk. Oral presentation, Hamlet of Paulatuk, Paulatuk, NT.
- Lede, E. (2018). Change? What Change?. Oral presentation, Angik School, Paulatuk, NT.
- Lede, E., Pearce, T., Fawcett, D. (2018). The human face of climate change in the Inuvialuit Settlement Region. Oral presentations, Inuvialuit Regional Corporation, Inuvialuit Cultural Resource Centre, and Aurora Research Institute, Inuvik, NT.
- Pearce, T. (2017). What is sustainability anyway? Invited presentation to Mountain Creek High School Grade 11 &12 students. 15 February 2017. University of the Sunshine Coast, Queensland, Australia.
- Pearce, T. (2018). What is science? Inuit and western science to understand climate change. Presentation to high school students at Helen Kalvak Elihakvik. 30 January 2018. Ulukhaktok, NT, Canada.
- Pearce, T. (2018). Hunting under changing conditions - research updates. Presentation to the Ulukhaktok Community Corporation (UCC). 17 January 2018. Ulukhaktok, NT, Canada.
- Waugh, D. (2017). Inuvialuit Traditional Ecological Knowledge (TEK) of beluga whale (Delphinapterus leucas) in a changing climate in Tuktoyaktuk, NT. Dissemination Booklet.

Media

- Arctic Deeply. UAV uses for Search and Rescue in the Arctic (2017). https://arcticportal.org/ap-library/arctic-deeply/1949-robots-to-the-rescue-drones-could-help-with-arctic-search-operations.
- CTV News. A report on the progress of Climate Change Adaptation in Nunavut. https://www.ctvnews.ca/sci-tech/few-examples-of-concrete-action-study-says-nunavut-climate-adaptation-slow-1.3251977.
- Royal Canadian Air Force circular. (2017). 424 Arctic SAR mission. http://ontario.casara.ca/2017/08/01/casara-accompanies-424-squadron-arctic-mission/.

Other

- Dylan Clark was one of two witnesses to testify on the current state of search and rescue in the Arctic for the Senate Sub-Committee on Fisheries and Oceans.
- Galappaththi, E. and Flynn, M. (2017). ArcticNet Student Association. Student Day Panelists. Arctic Research for International students.
- Dylan Clark and Melanie Flynn co-organized alongside other students a two-day conference for young researchers working with Arctic communities.
- Fawcett, D. (March 2018). Climate change and food security in the Canadian Arctic. Presentation to Geography 140: Human Geography, University of the Fraser Valley.

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

Objectives 1 & 2: Conceptual development and methodological development

The majority of articles pertaining to these two objectives have been published. Building upon the conceptual model which has guided empirical research, in the last year we have also been pioneering a new multiplex network analysis approach to developing vulnerability indicators for the whole Inuit Nunangat. While not originally noted in the proposal, this activity reflects the overarching goal of this project to advance new approaches to vulnerability assessment in the north, combined with the opportunity presented by Drs. Debortoli and Sayles joining Prof. Ford's research group. A paper from this is under review at Env Research Letters (Debortoli et al., in review). PhD student Eranga Galappaththi also passed his comprehensive exams in the spring, with his work pioneering the integration of vulnerability and resilience approaches to understand how climate change interacts with Inuit fisheries. He aims to finish this by spring, with a conceptual paper to be submitted to a journal for peer review. A broader paper examining the state of the climate vulnerability field and which has informed development of this objective is under review at Climatic Change (Ford et al., in review).

Objective 3: empirical application

In Arctic Bay, master's student, Lewis Archer conducted a longitudinal study of harvester's experiences and vulnerability to climate change. The study built on Prof. Ford's PhD work in the community 10 years prior, with the aim of assessing how climatic and social factors have changed over the period. We found that vulnerability of present-day Arctic Bay shifted, driven largely by changing socio-economic conditions. The simultaneous rise in the cost of living, limited employment opportunities, and restrictive hours for those in employment were found to exacerbate the risks associated with changing climatic conditions.

In Arviat, Dylan Clark built on his master's thesis by continuing to explore search and rescue capacity and links to climate change and health. Partnering with the Arviat Search and Rescue committee as well as the Qaujigiartiit Health Research Centre, Dylan looked at the potential for unmanned aerial vehicles (UAVs) to be used for search and rescue and hazard identification by community members. The project involved a month and a half in Arviat conducting focus groups, live testing, and observing search and rescue operations. We found that given weather conditions required for flight, training obligations, legal limitations, and a general lack of capacity that UAVs would likely not be beneficial at this time. A journal article is currently being prepared for submission.

Eranga Galapaththi's PhD research is examining opportunities for social-ecological resilience building and vulnerability reduction (i.e., adaptation) to change, focusing on the impacts of climate change on remote Indigenous fisher populations. The first field data collection period in Pangnirtung was held from May to August 2017. A mixed methods research design will employ the case study method as the primary research strategy. Data were collected through participant observation (2 months), semi-structured interviews (51 fishers), focus group discussions (3), key informant interviews (6), spot interviews (23), and a drawing workshop (n=7). The social-ecological systems (SES) approach was used to capture the interconnected nature of climate change impacts, with analysis of results currently under way.

David Fawcett's MA research focused on completion of a longitudinal climate change vulnerability assessment in Ulukhaktok, and the submission of a related manuscript, 'Inuit adaptability to changing environmental conditions over an 11-year period in Ulukhaktok, NT', to Polar Record for review on December 21st, 2017. He has also continued to work on offshoot research projects, including compiling the results from, and contributing to the development of manuscripts for projects that focus on the changing economics of subsistence activities in Ulukhaktok, and how climate governance and politics, especially wildlife management, has impacted the local subsistence and sport hunting economies. Beyond work on analysis and outputs, he also developed materials to share with the community of Ulukhaktok and other stakeholders and decision-makers. These include a plain-language visual research summary booklet and website. These materials have been shared in hard copy format with the Inuvialuit Game Council at the Inuvialuit Settlement Region Research Day in Whitehorse in September 2017, stakeholders in Yellowknife, NT (e.g. Health Canada) and community members in Ulukhaktok in January 2018, and with the Inuvialuit Regional Corporation, Inuvialuit Cultural Resource Centre, and Aurora Research Institute in Inuvik, NT in January 2018.

Eric Lede completed his masters thesis project focusing on Paulatuk, presenting his work at international conferences, regional organizations, community organizations and schools, and a Masters thesis. Presentations, both oral and poster formats, were conducted at the 2017 Arctic Change and the 2017 United Nations Climate Change Conference COP23, with the work disseminated to regional organizations within the Inuvialuit Settlement Region including the Inuvialuit Regional Corporation and the Inuvialuit Cultural Resource Centre. Dissemination of the research findings were conducted in January-February 2018 in Paulatuk, NT with a series of oral presentations and a dissemination summary booklet.

Melanie Flynn is building on her previous work around the use of participatory scenarios across the North American Arctic, and she is undertaking a PhD and is in the preliminary stages of co-creating a series of workshops alongside Nunatsiavut Government. The workshops will use participatory scenario approaches to create the Nunatsiavut Regional Food Security plan. Additionally, Melanie's work on knowledge mobilization has been used by the Northern Communities team at Ouranos to inform their work on 'Convergence of Traditional/Local and Scientific Knowledge of Climate Change in the North'. Melanie was also involved in the co-organization of a young researcher conference which focused on peer-to-peer learning, session themes included methodologies, knowledge mobilization, relationship building, wellness in research and project management strategies.

Objective 4: Adaptation planning

NIs on this ArcticNet project are also working on other ArcticNet projects, with a combined focus on adaptation to multiple stressors, a longitudinal approach to climate change vulnerability assessment, and previous projects focused on food security and climate change, and women's perceptions of health and climate change. Together, the results from these have been shared with stakeholders and decision-makers in the communities, at the regional level (e.g. Inuvialuit Regional Corporation), and at the federal level (e.g. Indigenous and Northern Affairs Canada (INAC) and Health Canada) so that they can be implemented into adaptation planning and policy. More specifically, the results from our projects in the ISR are helping to drive two separate funding applications by Ulukhaktok. One of these applications is to Health Canada for the Nunamin Illihakvia (learning from the land) program, which will focus on the transmission and generation of environmental knowledge, land skills, sewing and food preparation skills, and language in Ulukhaktok. This program will also include a feasibility study of the development of a cultural school, similar to Piqqusillirivvik in Clyde River, NU, for the whole of the ISR in Ulukhaktok. The other funding application by Ulukhaktok is to INAC for the Toniktoyak (extreme determination, or the determination to succeed) program that will involve community-researcher collaboration to document the changing costs of hunting, and how economics at the individual- and family-levels impact subsistence activities and how risk is encountered and experienced. This program will also include the development of an interactive map, similar to the Baffinland Atlas, for Ulukhaktok, by Ulukhaktok, and working with researchers from the University of Victoria to develop local weather forecasting that is more accurate and more relevant to community members.

In Nunavut, the PI (Ford), led a project to examine the adaptation landscape in Nunavut to examine the challenges and opportunities for adaptation actions.

Objective 5: Comparative analysis

A workshop will be held in 2018 for the different NIs and students engaged in the project to complete this objective. It will be externally funded.

RESULTS

Based on Dylan's research into the search and rescue capacity and potential UAV uses by Northern communities, we have outlined considerable limitations to emergency management at the community scale as well as the potential benefits and constraints of UAVs. We found that the emergency response capacity of communities is limited by financial and resource investments, such as a lack of first aid courses, boats and ATVs, and communication devices. We also found that emergency responders are generally underprepared for community disasters (such as a prolonged power outage or landslide), and ill-prepared for larger disasters such as a cruise ship or aviation incident. While UAVs were found to potentially be useful for hazard monitoring, their use as a tool during emergencies is generally restricted by legal regulations and community capacity.

Eranga's work in Pangnirtung documents changes experienced most keenly by Inuit fishers to include: changes in sea ice conditions, the implications of recently emerged species, including Capelin (*Mallotus villosus*), warm weather conditions and melting glaciers around mountains, and changes in Inuit cultural values. Inuit fishers respond to change individually as well as collectively. First, fishers share their catch with relatives and elders, especially those who are unable to fish and hunt. This strengthens community cohesion and food security. Second, technology such as Global Positioning Systems (GPSs), Very High Frequency (VHF) radios and advanced rifles for fishing/hunting minimise vulnerabilities related to climate change. Third, place-based attitudes and cultural identity help the Inuit live with change. Fourth, Inuit-owned fishery institutions such as Pang fisheries and Baffin Fisheries create employment and commercial fishing opportunities for local fishers. Finally, community members use various kinds of knowledge to face climate change. This includes local knowledge about fishing, traditional knowledge from elders and the co-produced knowledge of fishers.

The results from David's work in Ulukhaktok enhance our understanding of how climatic and non-climatic changes have interacted since 2005 to impact Inuit subsistence activities, including participation, efficiency, and safety, and highlight important areas for potential adaptation interventions. While there have been several prominent changes in the biophysical environment because of climate change, such as changing summer wind patterns and the continued decline of sea ice in the area, respondents emphasized that these changes, while challenging on their own, become problematic relative to the dynamic socio-economic environment; the socio-economic environment has a major effect on how climate change is experienced and responded to by individuals. In particular, adaptation to climatic changes is progressively being impacted by the increasing level of financial resources required for subsistence activities and the time requirements that these financial inputs demand. These time requirements ultimately conflict with subsistence participation and flexibility. As a result, we suggest that adaptation entry points in Ulukhaktok focus on socio-economic constraints to adaptive capacity in order to enhance access to subsistence and build community capacity. In particular, community members emphasized the importance of programs that focus on the transmission and generation of environmental knowledge, land skills, sewing and food preparation skills, and language skills, which will all build capacity for community members to continue to engage with the environment and changing conditions for the purpose of subsistence, which will remain important for the local economy, culture, and food security.

Eric's work focused on the role of multiple social-ecological stressors in adaptation to environmental change using lessons from a place-specific case study. We analyzed the stressors that participants identified as relevant and important to their lives and identify where climate change fits. We found that non-climatic stressors such as financial barriers to participating in land-based activities, an inflexible education system, housing overcrowding, lifestyle changes and substance abuse influence how people perceive climate change stressors, which influences adaptive responses. Participants are uncertain about the directional nature and longer-term consequences of some stressors, namely financial barriers to participating in land-based activities and an inflexible education system, and this results in a great deal of uncertainty for how to respond. Thus, individuals are choosing to respond differently to the same stressors with varying degrees of success. In some cases, adaptive responses have depleted resources needed to respond to other stressors, and reduced the overall resilience of the social-ecological system. This study suggests new ways in which vulnerability theory and practice can be advanced to show how societies may adapt to climate change in the context of other stressors. Knowledge of other stressors presents strategic policy entry points for supporting adaptation to climate change while also building longer-term resilience in the system.

Nathan's work developed a multiplex network analysis approach to determine how social and environmental variables interact among and within the key component of Inuit vulnerability to climate change. Informed by a systematic literature review of community-based vulnerability studies, we assessed relationships among 58 social and biophysical variables. We found several structurally important variables for the region that interact across the three dimensions of vulnerability; these include cost of living, poverty, and income. We also highlighted that physical variables, such as extreme weather events, floods, and storm surges are highly important to exposure. Our framework illustrates which variables should be used and how they can be calibrated to represent vulnerability of Inuit communities in a climate linked index. The method is transferable as an integrative means of understanding not only the direct causes of vulnerability, but also relations that are less tangible. The approach of multiplex network analysis may be a building block to ongoing development of vulnerability indices within the human dimensions of climate change field.

James's work examined the institutional factors constraining and enabling climate change adaptation in Nunavut, and the overall readiness of governing bodies and communities to develop, implement, and promote adaptation. In the Government of Nunavut, there have been notable developments around adaptation planning and examples of adaptation champions, but readiness for adaptation is challenged by a number of factors including the existence of pressing socio-economic problems, and institutional and governmental barriers. Federally, there is evidence of high-level leadership on adaptation, the creation of adaptation programs, and allocation of funds for adaptation, although the focus has been mostly on researching adaptation options as opposed to supporting actual actions or policy change. The 2016 Pan-Canadian Framework on Clean Growth and Climate Change, and increasing emphasis on climate change federally and in the Government of Nunavut, offer opportunities for advancing adaptation, but concrete steps are needed to ensure readiness is enhanced.

The results of Melanie's work on the use of participatory scenario approaches in Arctic settings identified a growing interest in the approach in Arctic research. The research identified several benefits including the inclusion of different ways of knowing, the potential for social learning and the flexibility of the approach for use across a broad range of sectors. The work will now be used to inform future planning work on food security. We will be evaluating the process and hope to add key lessons learned. In addition, Melanie's work on knowledge mobilization in Arctic research addressed the ongoing disconnect between knowledge creators and users. The work identified six key principles of effective knowledge mobilization, including: understanding protocol, creating meaningful relationships, adapting communication modes, incorporating different ways of knowing, valuing knowledge mobilization and reconciling research. The next stage of this research involves empirically applying this framework and identifying barriers to effective knowledge mobilization and potential solutions.

DISCUSSION

This ArcticNet project has contributed to advancing our understanding of how climate change interacts with Inuit communities, affecting land based dangers and resource management. The work has made major conceptual and methodological contributions to how we study climate vulnerability in an era of rapid change, with publications in high impact international journals to this end. The work has helped to catalyze new foci in vulnerability research around monitoring human-environment interactions, with the empirical research challenging previous results while supporting others. For instance, across the communities we find that the main drivers of climate vulnerability are non-climatic, including weakening of land skills among younger generations, challenges associated with high food and housing insecurity, and colonial legacies. These drivers of vulnerability offer opportunities for adaptation policy. We also find that communities are adapting to change autonomously, but unlike other research we find that some of these adaptations may actually increase vulnerability in the long-term. Across communities, Indigenous knowledge systems underpin adaptability to change, and are evolving in-light of rapid climate change and emergence of new risks. Indeed, such knowledge is not being made obsolete in-light of climate change as some have argued. A bigger challenge is how such knowledge systems will evolve in-light of social, economic, and demographic changes facing northern communities.

While the work conducted under this ArcticNet project has significant advanced our understanding on climate vulnerability, advancing baseline work conducted in ArcticNet phase 1 to 3, much still remains to be done to fully capture 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 spatial-temporal scales; system feedbacks to stresses encountered; internal dynamics that give rise to new risks/enhance resilience; and critical interactions creating or moderating vulnerability. Furthermore, there is a need to parametrize key risks facing communities to better link to climate modeling efforts, and bridge top down and bottom up approaches to climate vulnerability assessment. New funding is being sought to address these gaps in knowledge not only in Inuit regions of Canada, but also in Alaska and Greenland.

CONCLUSION

The Canadian Arctic is a global hotspot of climate change impacts. This research program has expanded our understanding of what makes communities vulnerable or resilient to the impacts of climate change. Focusing specifically on the Inuit harvesting sector and land use associated with this, the program developed a longitudinal community-based monitoring approach which involved 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 long-term collaboration, the findings of the work helped us examine and test conclusions reached by other studies, including our own. The work shows that climate change vulnerability is highly dynamic, continually changing evolving as the climate and society changes. Non-climatic factors are the main determinants of vulnerability, increasing or moderating sensitivity and adaptive capacity to climate risks. These non-climatic factors, particularly the importance of Indigenous knowledge systems, offer entry points for adaptation actions.

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REFERENCES AND PUBLICATIONS

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.

Carter, J. Pearce, T., Jacobsen, C. (In press - Jan 2018). Working the academy: a form of giving back. In: Douglas, H. (ed.) Giving Back. Smithsonian Institute, 23p.

Clark, D., and Ford, J. (2017). Emergency response in a rapidly changing Arctic. Canadian Medical Association Journal, 189(4).

Collings, P., Pearce, T., and Kann, J. (In press - Dec 2017) Inuit conceptions of ‘knowing’ and ‘ecological knowledge’ about beluga whales in Ulukhaktok, NT, Canada. Arctic Science, 28p.

Debortoli, N., Sayles, J., Clark, D., Ford, J. (in review) A systems network approach for climate change vulnerability assessment. Environmental Research Letters.

Fawcett, D. (2017) A longitudinal approach to climate change vulnerability assessment in Ulukhaktok, NT. Thesis, University of Guelph.

Fawcett, D., Pearce, T., Ford, J. Archer, L. (2017). Operationalizing Longitudinal Approaches to Climate Change Vulnerability Assessment. Global Environmental Change 45, 79-88.

Fawcett, D., Pearce, T., Notaina, R., Ford, J.D., Collings, P. (In review - Dec 2017) Inuit adaptability to changing environmental conditions over an 11-year period in Ulukhaktok, NT. Polar Record.

Flynn, M., Ford, J., Pearce, T., Harper, S., IHACC Research Team. (2018). Participatory scenario planning and climate change impacts, adaptation, and vulnerability research in the Arctic. Environmental Science and Policy, 79, 45-53.

Ford, J., Bell, T., Couture, N, Clark, D. (2018) Climate change and Canada’s northern coast: Current knowledge, future research needs. Environmental Reviews.

Ford, J., Falk, K., Tesar, C. Adaptation and resilience. Chapter 11 in Adaptation Actions for a Changing Arctic Assessment, Arctic Council.

Ford, J., Labbe, J., Flynn, M., IHACC Research Team. (2017). Readiness for climate change adaptation in Nunavut, Canada. Climatic Change, 145(1-2), 85-100.

Ford, J., Pearce, T., McDowell, G., Berrang-Ford, L., Sayles, J. (in review) Vulnerability science and its discontents. Climatic Change.

Hoover, C., Ostertag, S., Hornby, C., Parker, C., Hansen-Craik, K., Loseto, L., Pearce, T. (2017). The continued importance of the hunter for Inuit food security. Solutions.

Labbe, J., Ford, J., Araos, M., and Flynn, M. (2017). The government-led climate change adaptation landscape in Nunavut, Canada. Environmental Reviews, 25(1), 12-25.

Lede, E. (2018). Adaptation to climate change in the context of multiple stressors in the Canadian Arctic. Thesis, University of the Sunshine Coast (Australia).

Lede, E., Pearce, T., Furgal, C., Ford, J. (In review - 2018) Hacking adaptation: the role of multiple stressors in adaptation to climate change in the Arctic. Ecology and Society.

Pearce T. (2018). Human Health Adaptations in Canada. In: Trainor, S.F. (ed.), Chapter 7: Adaptation, Adaptation Actions for a Changing Arctic: perspectives from the Bering-Chukchi-Beaufort Region, Arctic Monitoring and Assessment Program (AMAP). Huntington, H.P. and Eerkes-Medrana, L. (eds.): 185-186.

Pearce T. (2018). Inuit subsistence hunting and climate change: Ulukhaktok, NWT, Canada. In: Huntington, H.P., and Eerkes-Medrana, L. (eds.), Chapter 2: Stakeholder Perspectives, Adaptation Actions for a Changing Arctic: perspectives from the Bering-Chukchi-Beaufort Region, Arctic Monitoring and Assessment Program (AMAP): 20-21.

Pearce, T. (In press - Dec 2017) Incorporating Indigenous knowledge in research. In: McLeman, R., and Gemenne, F. (eds.) Routledge Handbook on Environmental Displacement and Migration. Routledge.

Waugh, D. (2018). Inuvialuit Traditional Ecological Knowledge (TEK) of beluga whale (*Delphinaterus leucas*) in a changing climate in Tuktoyaktuk, NT. Thesis, University of Guelph.

Waugh, D., Pearce, T., Ostertag, S., Collings, P., Loseto, L. (In press - Dec 2017) Inuvialuit traditional ecological knowledge of beluga whale (*Delphinapterus leucas*) under changing climatic conditions in Tuktoyaktuk, NT. Arctic Science, 22p.

Wright, C., Sergeant, J., Edge, V., Ford, J. et al. (2017). How are Perceptions Associated with Water Consumption in Canadian Inuit? A Cross-sectional Survey in Rigolet, Labrador. Science of the Total Environment 618, 369-378.

FOODBORNE AND WATERBORNE DISEASE MITIGATION: COMMUNITY-BASED SURVEILLANCE FOR ENVIRONMENTAL HEALTH

Project Team

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ABSTRACT

Globally, the highest rates of self-reported enteric illness (i.e., diarrhea and vomiting) have been reported in Iqaluit, Nunavut. Infectious diarrhea and vomiting can be caused by contaminated drinking water (i.e., waterborne disease), contaminated food (i.e., foodborne disease), or person-to-person contact. To reduce the high rates of diarrhea and vomiting in Northern Canada, we must identify and monitor the pathogens causing illness. This process will help us better 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 better understand whether or not food and water contamination is causing illness in people in Iqaluit, Canada. 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. 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 aimed 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) from June to September 2016. Using microscopy, 20.0% of samples tested positive for *Giardia* and 1.8% of samples tested positive for *Cryptosporidium*, although pathogen species could not be identified. Among positive samples, the average concentrations were 1.3 *Giardia* cysts/100 L and 0.9 *Cryptosporidium* oocysts/100 L indicator bacteria (*E. coli* & total coliforms) were not significantly associated with presence of parasites. Low water temperatures (1.1 to 6.7°C; OR = 4.07; 95% CI = 0.89-22.11) and low air temperatures (-0.1 to 4.5°C; OR= 4.43; 95% CI = 0.93-25.13) were significantly associated with increased odds of parasites compared to higher temperatures.
- Pet Stool Sampling and Testing: Canine fecal samples (N=452) were collected in Iqaluit from sled dogs, dogs from the local humane society, and samples found in the environment. Sled dogs: In July 2016, 30% of sampled dogs were positive for *Giardia*; 30% were positive for *Cryptosporidium*. In September 2016, 17% of dogs were positive for *Giardia*; 24% were positive for *Cryptosporidium*. Humane society: In September 2016, 0.9% of sampled dogs tested positive for *Giardia*; 4.5% tested positive for *Cryptosporidium*. Environmental samples: In September 2016, 3.8% of samples tested positive for *Giardia*; 4.8% tested positive for *Cryptosporidium*.
- Clam Sampling and Testing: Clams (N=404) were collected from local harvesters in Iqaluit in Summer 2016. The clams were processed on-site in Iqaluit, and tested in year 3 at the University of California Davis and University of Guelph for parasite presence/absence. Prevalence of *Giardia* was 0.5% (2/396); no samples tested positive for *Cryptosporidium*.
- In Year 3, we
    - » Completed sample processing and trained an undergraduate student in lab methods for testing clams;
    - » Completed quantitative statistical analyses;
    - » Shared project results with research partners, government and public health authorities in Iqaluit (including the Government of Nunavut, Indigenous and Northern Affairs Canada, and the Nunavut Research Institute), and are working in collaboration to roll out a result sharing campaign in Iqaluit in March 2018;
    - » Presented 12 oral and poster presentations at academic forums/conferences;

   - Published 3 research articles, submitted 1 to an academic journal for peer-review, and anticipate submission of 5 more in 2018; and
   - Anticipate completion of 2 MSc and 1 PhD theses.

- The project allowed us to build new relationships with eight key academic and government collaborators over the course of this project, spanning multiple disciplines (epidemiology, microbiology, social sciences, veterinary medicine, human medicine), locales (Nunavut, Ontario, Quebec, Newfoundland and Labrador, California, Alberta), and sectors (academia, government, non-government organizations, and the private sector). We expanded our research partnerships, refined the surveillance concept and methods, and increased matching funds. Knowledge translation activities at every stage of the research process (from research question identification to the current results sharing campaign for the community of Iqaluit) was critical to ensure that our research will produce interventionable results that align with northern priorities.
- We ensured that our research questions, study design, data collection methods, preliminary interpretation of the results, and overall approach helped meet northern priorities, and were locally appropriate and culturally sensitive. Understanding and respecting the social, cultural, and environmental constructs and pathways through which foodborne and waterborne pathogens could be transmitted was key to developing a surveillance system that respects and reflects Inuit culture, and provides the necessary information to identify and control disease.

RESEARCH OBJECTIVES

Project Goal: Develop a participatory, community based surveillance system to understand, respond to, and reduce the burden of illness from foodborne, waterborne, and zoonotic pathogens in Iqaluit.

In Year 3, we continued to pursue and complete the objectives outlined in our proposal:

1. Establish a transdisciplinary team: Over the course of the project, we 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, surveilled enteric pathogens, and will continue to work together as partners through the results sharing process. Our team has grown continuously and gained valuable expertise 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. Through this project we examined 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 estimated the prevalence, identifies risk factors, and examined 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.

4. Conduct effective knowledge translation and extension (KTE): Ongoing and meaningful collaboration with Inuit stakeholders, health professionals, and Inuit organizations is essential to developing and evaluating a culturally acceptable and effective knowledge translation program to reduce foodborne, waterborne, and zoonotic enteric illness. Our end users believe that the information gleaned from this study is critical for developing or enhancing existing public health planning, programming, and policy to effectively reduce the high reported burden of enteric illness.

KNOWLEDGE MOBILIZATION

- Results sharing meeting with northern, federal, & territorial stakeholders (n=19 representatives): In-person meeting in Iqaluit (November 2017) with representatives from:
  - » The Public Health Agency of Canada;
  - » Nunavut Research Institute;
  - » Government of Nunavut Department of Health;
  - » Indigenous and Northern Affairs Canada;
  - » University of Guelph; and
  - » The Centre for Public Health & Zoonoses
- 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.
- 11 side meetings at ArcticNet Annual Scientific Meeting: We held and/or participated in 11 side-meetings with Northern stakeholders, southern academics, and government representatives.
- 5 Media Interviews: 3 online news articles (Ontario Veterinary College, Nunatsiaq News, and CBC North); 2 televised interviews (Aboriginal People's Network and CBC North).
- 25 abstracts, conference presentations, and scholarly posters: Results were shared by researchers, HQP, and Northern partners at conferences within Canada and abroad, including the annual ArcticNet Annual Scientific Meeting.
- 4 scholarly articles published or in review, and 5 anticipated manuscripts for submission in 2018.
- 1 active website: research website disseminates project outputs, including videos, updates on project progress, and research results (including results dissemination activities).

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 & 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 & Empirical Research: Collect and analyze surveillance data. (Years 2-3; completed).
- Phase 3 - Comparative Analysis: Examine similarities and differences between communities and other locales. (Year 3; completed).
- Phase 4 - Knowledge Translation and Exchange (KTE): Develop locally-appropriate and culturally-relevant knowledge translation techniques. (Years 1-3; anticipated completion by end of 2017/18 fiscal year).
- 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.
- Focus of Year 3: In Year 3, we completed our planned activities, milestones, and project deliverables, which primarily focused on comparative analyses, as outlined in our proposal. At the end of Year 3 we expect we transitioned our focus to Data Collection and Empirical Research (Phase 2).

Collaboration and Engagement (Year 3)

- Results sharing meeting with northern, federal, & territorial stakeholders (n=19 representatives): An In-person meeting in Iqaluit took place in November 2017, to share results of this project with stakeholders from Nunavut and discuss results sharing with the general public. The meeting included representatives from:
  - » The Public Health Agency of Canada;
  - » Nunavut Research Institute;
  - » Qaujigiartiit Health Research Centre
  - » Nunavut Tunngavik
  - » Government of Nunavut Department of Health;
  - » Indigenous and Northern Affairs Canada;
  - » Department of Population Medicine, University of Guelph; and
  - » The Centre for Public Health & Zoonoses, University of Guelph
- Side Meeting at the 2017 ArcticNet Annual Scientific Meeting: Team members attended a dog-focused side meeting and networked with public health officials, veterinarians, and government officials from across Northern Canada (Including Nunavik, Nunavut, and Northwest Territories).
- Outcome: Through meaningful collaboration with our northern partners, we completed surveillance activities for the project and are developing a larger scale results dissemination plan for the City of Iqaluit.

Qualitative Data Analysis (Year 3)

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.

Quantitative Data Analysis (Year 3)

- In consultation with Northern stakeholders, the quantitative research questions, study design, data collection and analysis procedures were developed.
- Data analysis was completed in late 2017.
- Canine Stool Testing: High caliber graduate students collected the data and completed lab analyses (PhD Candidate: Dr. Danielle Julien (DVM, MPH). In Year 3, samples were analyzed using rapid immunoassay and flotation techniques. Polymerase chain reaction (PCR) and sequencing of target genes was performed on positive samples (n=25 for *Giardia*; n=33 for *Cryptosporidium*) for zoonotic evaluation to identify parasite species and assemblages. Statistical analyses to identify risk factors for parasite presence in dog stool samples was

completed by Dr. Julien under supervision of Dr. Jan Sargeant and Dr. Sherilee Harper.

- Clam Testing: MSc Candidate Anna Manore examined enteric pathogens in locally harvested clams (N=404). In Year 3, samples were processed to retrieve hemolymph and digestive gland fluid on-site. Part of the analysis was conducted at the University of California Davis under supervision of Dr. Karen Shapiro, an expert in zoonotic pathogens of watersheds and coastal ecosystems. Lab processing was completed at the Centre for Public Health and Zoonoses at the University of Guelph in Summer 2017. Samples underwent standard detection methods and molecular analysis to provide an estimate of the prevalence of *Giardia* and *Cryptosporidium*. Descriptive analyses of parasite prevalence and locations of detection have been completed.
- Water Testing: MSc Candidate Stephanie Masina worked closely with Jamal Shirley (Nunavut Research Institute) to examine coliforms, *Cryptosporidium*, and *Giardia* in surface water in Iqaluit. Data collection and preliminary analyses were completed in Year 2. In Year 3, data were analyzed further using exact logistic regression to identify factors associated with presence of parasites in water, under supervision of Dr. Sherilee Harper.

Communications (Year 3)

- Abstracts, conference presentations, and scholarly posters: 12 academic presentations by researchers, HQP, and northern partners were given at conferences within Canada and abroad, including the annual ArcticNet Annual Scientific Meeting in December 2017. See publication list for details.
- Scholarly articles: 3 articles published and 1 submitted to a journal. Five further articles are anticipated.
- Active website: A research website disseminates project outputs, including videos, updates on project progress, research results, and results dissemination activities.
- Training and development: HQP training in laboratory methods, statistical data analysis, and communications.
- Matching Funds (Year 3): In Year 3 we secured additional matching funds, leveraging over two-times the funds received from ArcticNet NCE.

RESULTS

Below are selected key results from our ArcticNet funded work from Years 2-3.

A community-based foodborne, waterborne, and zoonotic enteric disease surveillance plan was developed and 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 collaborated with Drs. Goldfarb and Yansouni to understand and compare prevalence of these parasites in humans. While we are focusing on Giardia and *Cryptosporidium* in this project, we have stored samples for future testing of other pathogens when funds become available. While a number of pathogens and environmental exposures were considered, extensive stakeholder engagement determined that our surveillance program would involve testing *Giardia* and *Cryptosporidium* in dog stool, surface water, and locally-harvested clams.

Prevalence of positive samples and risk factors for presence of parasites

- Dogs: There were 60 samples collected from 20 dogs during the July pilot test (1 sample per dog on 3 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 24% 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*. The odds of fecal *Giardia* spp. shedding varied significantly across dog groups sampled in September (OR=10.19; 95% CI 1.16-89.35). There was no association between dog group and fecal *Cryptosporidium* spp., shedding for the same period.
- Food: There were 404 clams collected from local harvesters in Iqaluit in Summer 2016; hemolymph was extracted from 328 clams, and digestive gland was extracted from 390 clams (note that these differences were due to inability to retrieve either hemolymph and/or digestive gland from some clams). Prevalence of *Giardia* was 0.6% (2/328); Prevalence of *Cryptosporidium* was 0% (no samples tested positive). Due to the low number of samples that tested positive for parasites (n=2), regression modelling to identify risk factors for parasite presence was not possible.
- Water: Surface water samples were collected from Sylvia Grinnell River (n=24), Apex River (n=26), and Carney Creek (n=5) from June to September 2016. Using microscopy, 20.0% of samples tested positive for *Giardia* and 1.8% of samples tested positive for *Cryptosporidium*, although pathogen species could not be identified. Among positive samples, the average concentrations were 1.3 *Giardia* cysts/100 L and 0.9 *Cryptosporidium* oocysts/100 L indicator bacteria (*E. coli* & total coliforms) were not significantly associated with presence of parasites. Low water temperatures (1.1 to 6.7°C; OR = 4.07; 95% CI = 0.89-22.11) and low air temperatures (-0.1 to 4.5°C; OR= 4.43; 95% CI = 0.93-25.13) were significantly associated with increased odds of parasites compared to higher temperatures.

Source Attribution

- Dogs: Amplified *Giardia* and *Cryptosporidium*. DNA was detected in 7/25 (28.0%) and 19/33 (57.6%) samples that tested positive in the rapid immunoassay and/or fecal flotation techniques, respectively. Sequence analysis revealed that 6 samples were *Giardia* intestinalis, assemblages B (n=2), D (n=3) and E (n=1); 5 amplicons had 100% homology for *Cryptosporidium* canis.
- Water: *Giardia* and *Cryptosporidium* DNA was not detected in any of the water samples processed with PCR, thereby precluding identification of species and genotypes; however, microscopy revealed presence of *Giardia* cysts and *Cryptosporidium* oocysts, leading us to conclude that the parasites' genetic material was either damaged by time of testing, or present in quantities too small to detect using PCR.
- Food: Both positive samples positive for *Giardia* were determined to be *Giardia* duodenalis assemblage B. *Genetic* sequencing revealed that the two positive *Giardia* samples contained two single nucleotide polymorphisms (SNPs), making them slightly different from *Giardia* sequences reported elsewhere.

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 and analyses in Year 3 was intended to test several hypotheses. Stakeholder's 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 rarely been conducted for parasites. While we were not able to identify specific species or genotypes of *Giardia* and *Cryptosporidium* in this study, this work has contributed to limited literature on these parasites in the North, and increases our understanding of waterborne risks in the Arctic. Furthermore, considering the relatively limited media coverage of Arctic water security, in this project 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 hypothesized 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, and the discovery of Giardia intestinalis assemblage B in two dog stool samples provides a base of support for this hypothesis in the Arctic. Continued monitoring of dogs for fecal shedding of *Cryptosporidium* and *Giardia* will help increase understanding the extent to which 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 to estimate the prevalence and risk factors associated with parasite presence in water, dogs, and clams. Our surveillance design is grounded in scientific evidence and Inuit traditional knowledge, provides data that are comparable to national surveillance programs, and is culturally appropriate and locally relevant. We are ending Year 3, and the final phase of the project, on schedule. Data analysis is complete, and results have been shared with northern stakeholders. A public results sharing campaign is underway. We have completed Year 3 project milestones and deliverables (as outlined in our proposal).

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REFERENCES

1. WHO. (2009). Global Health Risk Summary Tables. Health Statistics and Informatics Department, World Health Organization, Geneva, Switzerland.
2. Kovats, R.S., Edwards, S.J., Charron, D., Cowden, J., D'Souza, R.M., Ebi, K.L., Gauci, C., Gerner-Smidt, P., Hajat, S., Hales, S., Hernández Pezzi, G., Kriz, B., Kutsar, K., McKeown, P., Mellou, K., Menne, B., O'Brien, S., Pelt, W., and Van Schmid, H. (2005). Climate Variability and *Campylobacter* Infection: An International Study. International Journal of Biometeorology. 49(4), 207–214.
3. Charron, D.F. (2009). Potential Impacts of Global Warming and Climate Change on The Epidemiology of Zoonotic Diseases in Canada. Canadian Journal of Public Health. 93(5), 334–335.
4. Charron, D., Thomas, M., Waltner-Toews, D., Aramini, J., Edge, T., Kent, R., Maarouf, A., and Wilson, J. (2007). Vulnerability of Waterborne Diseases to Climate Change in Canada: A Review. Journal of Toxicology and Environmental Health. 67(20–22),1667–77.
5. Fleury, M., Charron, D.F., Holt, J.D., Allen, O.B., and Maarouf, A.R. (2006). A Time Series Analysis of the Relationship of Ambient Temperature and Common Bacterial Enteric Infections in Two Canadian Provinces. International Journal of Biometeorology. 50(6),385–91.
6. Costello, A., Abbas, M., Allen, A., Ball, S., Bell, S., Bellamy, R., Friel, S., Groce, N., Johnson, A., Kett, M., Lee, M., Levy, C., Maslin, M., McCoy, D., McGuire, B., Montgomery, H., Napier, D., Pagel, C., Patel, J., Oliveira, J.A.P. de, Redclift, N., Rees, H., Rogger, D., Scott, J., Stephenson, J., Twigg, J., Wolff, J., and Patterson, C. (2009). Managing the Health Effects of Climate Change. Lancet. 373(9676),1693–733.
7. Harper, S.L. (2014). Gastrointestinal Illness in Canada's North: Implications of Climate Change on Current and Future Inuit Health. PhD Thesis Dissertation.
8. Majowicz, S.E., Doré, K., Flint, J.A., Edge, V.L., Read, S., Buffett, M.C., McEwen, S.A., McNab, W.B., Stacey, D., Sockett, P., and Wilson, J.B. (2004). Magnitude and Distribution of Acute, Self-reported Gastrointestinal Illness in a Canadian Community. Epidemiology and Infection. 132(4), 607–617.
9. Sargeant, J.M., Majowic, S.E., and Snelgrove, J. (2008). The Burden of Acute Gastrointestinal Illness in Ontario, Canada, 2005-2006. Epidemiology and Infection. 136(4), 451–460.

10. Thomas, M.K., Majowicz, S.E., MacDougall, L., Sockett, P.N., Kovacs, S.J., Fyfe, M., Edge, V.L., Doré, K., Flint, J., Henson, S., and Jones, A.Q. (2006). Population Distribution and Burden of Acute Gastrointestinal Illness in British Columbia, Canada. BMC Public Health. 6, 307.

11. Henson, S.J., Majowicz, S.E., Masakure, O., Sockett, P.N., MacDougall, L., Edge, V.L., Thomas, M.K., Fyfe, M., Kovacs, S.J., and Jones, A.Q. (2008). Estimation of the Costs of Acute Gastrointestinal Illness in British Columbia, Canada. International Journal of Food Microbiology. 127, 43–52.

12. Scallan, E., Majowicz, S.E., Hall, G., Banerjee, A., Bowman, C.L., Daly, L., Jones, T., Kirk, M.D., Fitzgerald, M., and Angulo, F.J. (2005). Prevalence of Diarrhoea in the Community in Australia, Canada, Ireland, and the United States. International Journal of Epidemiology. 2005;34(2):454–460.

13. Roy, S.L., Beach, M.J., and Scallan, E. (2006). The Rate of Acute Gastrointestinal Illness in Developed Countries. Journal of Water and Health. 4(Suppl 2), 31–69.

14. Jones, T.F., McMillian, M.B., Scallan, E., Frenzen, P.D., Cronquist, A.B., Thomas, S., and Angulo, F.J. (2007). A Population-based Estimate of the Substantial Burden of Diarrhoeal Disease in the United States; FoodNet, 1996-2003. Epidemiology and Infection. 135(2), 293–301.

15. Public Health Agency of Canada. (2006). Enteric Disease: A Major Health Concern in Canada.

16. Thomas MK, Majowicz SE, Pollari F, and Sockett PN. (2008). Burden of Acute Gastrointestinal Illness in Canada, 1999-2007: Interim Summary of NSAGI Activities. Canada Communicable Disease Report. 34(5), 8–15.

17. Young, K., and Chatwood, S. (2011). Health Care in the North: What Canada Can Learn from Its Circumpolar Neighbours. Canadian Journal of Public Health. 183(2), 209–214.

18. Adelson, N. (2005). The Embodiment of Inequity: Health Disparities in Aboriginal Canada. Canadian Journal of Public Health. 96, S45-61.

19. King, M. (2009). An Overall Approach to Health Care for Indigenous Peoples. Pediatric Clinic of North America. 56(6),1239–42.

20. Gracey, M., and King, M., (2009). Indigenous Health Part 1: Determinants and Disease Patterns. Lancet. 374(9683), 65–75.

21. Ford, J.D., Berrang-Ford, L., King, M., and Furgal, C. (2010). Vulnerability of Aboriginal Health Systems in Canada to Climate Change. Global Environmental Change. 20(4), 668–680.

22. Ford JD. (2012). Indigenous Health and Climate Change. American Journal of Public Health. 102(7),1260–1266.

23. King, M., Smith, A., and Gracey, M. (2009). Indigenous Health Part 2: The Underlying Causes of the Health Gap. Lancet. 374(9683), 76–85.

24. Knotsch K., and Kinnon D. (2011). If Not Now .... When? Addressing the Ongoing Inuit Housing Crisis.

25. Pardhan-Ali, A., Berke, O., Wilson, J., Edge, V.L., Furgal, C., Reid-Smith, R., Santos, M., and Mcewen, S.A. (2012). A Spatial and Temporal Analysis of Notifiable Gastrointestinal Illness in the Northwest Territories, Canada, 1991-2008. International Journal of Health Geography. 11(17).

26. Pardhan-Ali, A., Wilson, J., Edge, V.L., Furgal, C., Reid-Smith, R., Santos, M., and McEwen, S.A. (2013). Community-Level Risk Factors for Notifiable Gastrointestinal Illness in the Northwest Territories, Canada, 1991-2008. BMC Public Health. 13, 63.

27. Pardhan-Ali, A., Wilson, J., Edge, V.L., Furgal, C., Reid-Smith, R., Santos, M., and

McEwen, S.A. (2012). A Descriptive Analysis of Notifiable Gastrointestinal Illness in the Northwest Territories, Canada, 1991-2008. BMJ Open.2(4).

28. Pufall, E.L., Jones, A.Q., McEwen, S., Lyall, C., Peregrine, A.S., and Edge, V.L. (2011). Community-derived Research Dissemination Strategies in an Inuit Community. International Journal of Circumpolar Health. 70(5), 532–541.
29. Pufall, E.L., Jones, A.Q., McEwen, S.A., Lyall, C., Peregrine, A.S., and Edge, V.L. (2011). Perception of the Importance of Traditional Country Foods to the Physical, Mental, and Spiritual Health of Labrador Inuit. Arctic. 64(2), 242–250.
30. Pufall, E.L., Jones-Bitton, A., McEwen, S.A., Brown, T.M., Edge, V.L., Rokicki, J., Karpiej, K., Peregrine, A.S., and Simard, M. (2012). Prevalence of zoonotic Anisakid nematodes in Inuit-harvested fish and mammals from the eastern Canadian Arctic. Foodborne Pathogens and Disease. 9(11), 1002-1009.

PUBLICATIONS

Lam, S., Cunsolo, A., Sawatzky, A., Ford, J., and Harper, S.L., (2017). How Does the Media Portray Drinking Water Security in Indigenous Communities in Canada? An Analysis of Canadian Newspaper Coverage from 2000-2015. BMC Public Health.

Wright, C.J., Sargeant, J., Edge, V.L., Ford, J., Farahbakhsh, K., Shiwak, I., Flowers, C., Gordon, A.C., the Rigolet Inuit Community Government, IHACC Research Team, and Harper, S.L. (2018). How are Perceptions Associated with Water Consumption in Canadian Inuit? A Cross-sectional Survey in Rigolet, Labrador. Science of the Total Environment. 618, 369-378.

Wright, C.J., Sargeant, J.M., Edge, V.L., Ford, J.D., Farahbakhsh, K., RICG, Shiwak, I., Flowers, C., IHACC Research Team, Harper, S.L., (2017). Water Quality and Health in Northern Canada: Stored Drinking Water and Acute Gastrointestinal Illness in Labrador Inuit. Environmental Science and Pollution Research. 1-13.

NASIVVIK RESEARCH CHAIR IN ECOSYSTEM APPROACHES TO NORTHERN HEALTH

Project Team

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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, mercury (Hg) and lead (Pb) as well as older persistent organic pollutants (POPs) blood levels were low among participants aged 3 to 19 years old from four First Nation communities in Quebec. However, one more recent perfluorinated compound (PNFA), bisphenol A and monobenzyle phtalate were found to be elevated compared to the Canada general population at the same age.
- 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 and cobalt.
- 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 still presented blood Hg above the Health Canada guideline and sequential hair Hg analyses showed important regional and monthly variations in Hg exposure. Moreover, few participants still had blood Pb above the most recent level of concern. Conversely, all older POP exposures have decreased markedly excepted for more recent perfluorinated compounds. For example, time-trend analysis since 2012 showed that PFNA levels have increased by 15% and are higher than the Canada general population for women of childbearing age.
- Selenoneine, a potent anti-oxidant possibly acting against Hg toxicity, 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 and ranges in the United States. Conversely, this pathway of Nunavimmiut exposure to Pb appears negligible compared to the contamination of migratory birds flesh caused by the direct use Pb ammunition for hunting, and the related ingestion of Pb shots or fragments of Pb remaining in the flesh. These results also highlight that use of Pb-free ammunitions is the primary measure to protect Nunavimmiut from Pb exposure.

Human health effects of contaminants and contaminant/nutrient interactions

- POPs and Hg exposures modify the profiles of plasma metabolite related to cardiometabolic outcomes among Nunavik Inuit adults.
- High selenium (Se) status during pregnancy prevents Hg-related neurodevelopmental outcomes later at school age.
- Selenoneine was identified as the primary Se compound in red blood cells of Nunavimmiut adults, selenoneine levels were significantly higher among Inuit women and strongly associated to beluga mattaaq consumption after adjusting for all possible confounders.
- Elevated whole blood Se status among Arctic Inuit populations, as well as non-linear associations between whole blood Se and plasma Se found in Nunavik and Greenland, are likely due to accumulation of selenoneine in red blood cells resulting from consumption of marine country foods, and as result from beluga mattaaq and/or of other toothed-whale mattaaq consumption.

Conclusions

- Large screening for new emerging chemicals, including not only for those transported over long distances but also the less persistent ones from local sources, is important for better understanding the impact of local development and global dietary changes in Indigenous communities.
- Given the importance of local ecosystems and species to Inuit food security, there is a need for integrated systems-based modelling frameworks to assess the impact of global environmental processes (e.g. climate change and environmental contaminants) on local food environments, human health and wellbeing in the Arctic.

Considering the elevated levels of exposure to Hg, emerging chemicals and/or divalent metals, and prevalence of iron deficiency, anemia, obesity, diabetes and poor diet quality in younger indigenous populations, strong and rapid multilateral actions are needed to promote active livelihoods and land-based activities, healthy eating as well as safe traditional foods harvest and consumption.

RESEARCH 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 pursued the following Research Chair objectives:

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 zoonosis 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.
6. Mobilize knowledge into action:
    - Integrate, share, and discuss research outcomes with co-investigators, decision makers, key actors, and communities in northern regions.
    - Develop, implement, and evaluate projects, particularly with the youth and in close partnership with regional and local partners.

» Build the capacity of indigenous youth in health research, as well as practitioners working in health and social services, environment, and education sectors.

» Contribute to regional and national risk assessment initiatives and to implement public health policies.

» Participate 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 targeted 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 entitled 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 in the 2-day annual meeting of HHAG-AMAP and presentation 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 entitled 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 in the presence of Pierre Ayotte, Suzanne Bruneau and Chris Furgal, who 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 entitled "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 8 out of 9 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) co-signed by NNHC and Sarah Kalhok Bourque on behalf of the NCP Management Committee.
- August 2017: Community and health representatives' consultation in Iqaluit and Qikiqtarjuaq for the GreenEgde project.
- September 2017: Invited speaker at the NCP conference in Yellowknife.
- October 2017: Ducrocq (PhD student part of the Nasivvik Chair and awardee of the Mon projet nordique competition led by the FRQ) presented her PhD project at the Arctic Circle Assembly held in Reykjavik, Iceland.
- October 2017: Presentation of The Islands and the Whales documentary by Mike Day at the Departement de medicine sociale et preventive, ULaval.
- November 2017: Presentation of most recent research findings on selenoneine and from the NQN and BriGHT projects at the NNHC.
- November 2017: Presentation of most recent research findings on selenoneine and from the BriGHT project at the Annual General Meeting of the Regional Nunavimmi Umajulivijiit Katujiqatigininga (also known as Nunavik Hunting Fishing and Trapping Association or RNUK) in Tasiujaq.
- December 2017: Arctic Change conference in Quebec City: Joint Nasivvik Research Chair and Nasivvik Centre kiosk under the umbrella of the INQ and several presentations from members of the Nasivvik Chair.
- January 2018: Presentation of the latest project findings, student projects, and other Nasivvik chair activities at the NNHC meeting and review of 2018-2019 NCP proposals.
- February-March 2018: Host of the 48th HHAG-AMAP meeting in Quebec City on Feb 27 - March 1st. Organisation of public evening on March 1st to meet with AMAP delegates and NRBHSS practitioners followed by a presentation of the movie The Islands and the Whales featuring an HHAG-AMAP delegate, Pal Weihe from the Faroese Islands.
- March 2018: 3rd Nasivvik Chair Steering committee meeting in Quebec City.
- March 2018: Co-facilitation with Dr Poitras, dean of the Faculty of Medicine at ULaval, a panel entitled: "La recherche et les stages en santé mondiale : la réalité du terrain" during the 2018 Global Health meeting at Université Laval.
- March 2018: Invited speaker at the Université du Québec en Abitibi-Témiscamingue (UQAT) at the campus of Val d'Or to present our latest findings of the JES!-YEH! project.
- March 2018: Knowledge sharing and mobilisation activities in two anishinabeg communities involved in the JES!-YEH! project.

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, who 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 decreasing 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 the 1990s, Hg levels in human populations have also declined markedly. Between 1992 and 2013, Hg exposure have 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; Legrand et al. 2010). In First Nations communities in 2010, most adults presented low Hg exposure (Assembly of First Nations 2013). Since there is no evidence that Hg concentrations are actually decreasing in northern wildlife (Braune et al. 2015), this suggests that in most cases, this declining trend in human exposure is mostly due to reduced consumption of local foods (Adamou et al. In revision). The Minamata Convention on Hg emissions entered into force August 16, 2017 (http://mercuryconvention.org/Negotiations/COP1/tabid/5600/language/fr-CH/Default.aspx) and longitudinal environmental and human biomonitoring are needed to confirm future reductions of Hg 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 may also contribute to environmental contamination in the North. In addition, several other chemicals such new POPs and contaminants of emerging concern (CECs) (including new flame retardants, perfluorinated compounds, etc.) and less persistent chemicals such as bisphenol A and phtalates are presently found in northern ecosystems (AMAP 2016) and/or in several consumer goods, including possibly ultra-processed market foods (Zota et al. 2016). On top of this, once a specific contaminant becomes regulated, the chemical industry tends to replace it with a new molecule. Whereas some studies have documented environmental concentration of these more recent other contaminants in northern wildlife (AMAP 2016), few data are available regarding Indigenous communities and local workers exposures to these contaminants, particularly for CECs and less persistent chemicals, and their related-health outcomes (AMAP 2015; 2016).

Since 1999, lead (Pb) pellets are banned for hunting wildfowl in Canada and in the province of Quebec (ECCC 2016). However, Pb pellets are still widely used by hunters in Indigenous and non-Indigenous communities, even though Pb-free pellets are easily accessible (Pétrin-Desrosiers 2016). 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 of Pb bullets and are 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 animals hunted with Pb ammunitions and left on the land can 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 by 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 more food proportional to their weight than adults. Moreover, the foetus and children are also more sensitive to contaminants since most of these can cross the placental and blood-brain barriers and because their organs are still 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 current obesity and diabetes epidemics among First Nation communities (Sharp 2009).

Indigenous populations have preserved a very tight bond with 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 and 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. For example, iron (Fe) or selenium (Se) deficient status may lead to 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 ultra-processed market foods may lead to multiple-burden of diseases: overall poorer nutritional status, increased iron deficiency anemia, obesity and cardiometabolic diseases, and higher exposure and sensitivity to emerging environmental contaminants. Conversely, local traditional foods offer unique potential to bring together a range of knowledge aimed at promoting indigenous culture, preventing chronic illness and the effects of contaminants on health in the Arctic and other northern regions.

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; Y Yamashita et al. 2013). Selenoneine is a potent antioxidant that has been shown to accumulate in red blood cells together with Hg (M 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 other determinants, and health effects of selenoneine remain to be documented in Nunavik.

Another issue related to the 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 remains to 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 increased pressure on northern environments and affecting the health of northern populations in many ways. These include 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 and exerting an increasing pressure on local wildlife resources. Understanding the combined environmental/ecological, 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 was 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 a future 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 meeting related to the results of the project were held in 2017 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 currently organizing for the development of local action plans based on project findings to prevent childhood and youth iron deficiency and anemia, obesity and diabetes in First Nations communities in Quebec.

In 2017-2018, the research team focussed on completing descriptive analysis, coding nutritional intakes, analysing the data for Tahir's MSc project and writing the reports. The final reports of the results were provided to communities and Health Canada in 2017 – 2018 (see publication list). Data analysis for coding diet quality scores is ongoing. In March 2018, community meeting will be organised to present the latest findings of the project in the two anishinabeg participating communities.

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. In February 2018, Lemire, Chan at University of Ottawa, and Batal at Université de Montreal (Co-leaders of the FNFNES) were invited by the First Nations and Inuit Health Branch of the new Department of Indigenous Services Canada (DISC) to submit a proposal in May 2018 for this future pan-Canadian study. This multi-year project is envisioned to start in fall 2018.

Two Chair MSc students in this project:

<u>Emad Tahir's project</u> (2016-2018) is entitled: "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 Nation communities in Quebec" (Director: Lemire, Co-director: P Ayotte). Data analysis is ongoing and the manuscript is in preparation. 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 Axis of the CHU de Québec. Tahir also presented his preliminary findings the 29th Annual Scientific Conference of the

International Society for Environmental Epidemiology (CIHR travel grant) in Sept 2017 and at the Arctic Change conference in December 2017.

Claudelle Dubeau's project (2018-2019) is entitled: "Diet quality among children aged 3 to 19 from four First Nations communities in Quebec: associations with obesity, diabetes, anemia, thyroid status and exposure to contaminants from ultra-processed foods". She is currently writing her research protocol and data analysis will start shortly (Director: Lemire).

Chair postdoctoral fellow involved in the project:

Elyse Beaudoin-Caron's project (2018-2019) is entitled: "Elevated exposure to most recent perfluorinated compounds and obesity, diabetes and thyroid hormones imbalance among children aged from 3 to 19 years old from four First Nation communities in Quebec". She recently joined the team at part-time as a research assistant and she recently began analysing the data in preparation for a manuscript.

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, 2016-2019: $583K)

This four-year project aims to contribute to on-going international biomonitoring efforts on long-range environmental contaminants exposure among pregnant women in Nunavik and evaluate 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, POPs, polyunsaturated fatty acids (PUFAs) and iron biomarkers are now completed as well as the sequential hair analyses by centimetre for Hg. Analyses of selenoneine will be completed by March 2018. Individual results letters, both in English and Inuktitut, were sent by mail to all participants in June 2017. Additionally, if the participant consented, results were also sent to the health professional (doctor, midwife or nurse) involved in the women's pregnancy follow-up together with the Info-MADO newsletter written by Ricard and Lemire (see publication list).

A proposal for the third year of the project was submitted to the Northern Contaminants Program (NCP) last Jan 10, 2018. As childbearing-age women involved in Q2017 will be included in the present time-trends analysis, funds requested this year are mainly for the second part of the study (communication). Recruitment of pregnant women for biomonitoring activities will be conducted again in 2019.

Results of this project were regularly shared at the Nunavik Nutrition and Health Committee meetings (three times a year, by phone or in person in Kuujjuaq) and presented at Congrès nordique - À l'aurore de la santé boréale for Arctic health practitioners in Montreal in April 2017, at the Northern Contaminants Program 25th Anniversary and Results Workshop in Yellowknife in Sept 2017, and the Arctic Change conference last December 2017 (see publication list).

A paper is in revision for publication in Environment International: Adamou TY, Riva M, Muckle G, Anassour Laouan-Sidi E, Lemire M, Dery S, Ayotte P, 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 student in this project: Mariana de Moraes Pontual's project (2017-2018) is entitled: "Exposure to mercury through the food chain in Nunavik: geographical and temporal trends among pregnant women" (Director: Lemire). Her final protocol was accepted Jan 2018. Data analysis is on-going. Pontual presented her preliminary findings at the Arctic Change conference in December 2017.

Project Q2017: Qanuilirpitaa – How are we now? (Co-PI: Lemire, NCP funding for metals and long-range contaminants analysis, 2017-2019: $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 Nasivvik 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 fall 2016 - spring 2017, 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 was held in August-October on-board the Amundsen and a total of 1327 participants were recruited from the 14 communities of Nunavik. While Hg, Pb, Se and cadmium (Cd) are actually being 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 in pooled samples, individual analysis will be conducted. Algorithms for clinical follow-up of participants with elevated blood Hg or Pb levels are actually being finalised (See objective 6).

A proposal for the second year of the project was submitted to the NCP last Jan 10, 2018, in order to fund preliminary data analysis and subsequent legacy POPs, new POPs and CECs as well as selenoneine analysis in individual samples.

Nunavik country foods and selenoneine

Sources and distribution of selenium and selenoneine within the Arctic ecosystems (Co-PI: Lemire, NCP 2016-2017: $253K)

The main aim of this study is to determine total selenium (Se), selenoneine and essential fatty acids concentrations in a broad range of marine organisms selected based on their importance in terms of energy transfer in the Arctic ecosystems. During the last year, the analysis of two distinctive food webs (i.e. pelagic and benthic associated) for Se and selenoneine concentrations continued. Furthermore, samples were analysed and compared by stable isotope ($\delta^{15}N$, $\delta^{13}C$), highly branched isoprenoid (IP25) and fatty acid trophic marker (FATM) contents to gain insight on trophic interactions between species. Analyses took place at the Institut national de santé publique du Québec (INSPQ) and Laval University laboratories.

Chair MSc student in this project: Francis Dufour's project (2016-2018) is entitled: "Sources and distribution of selenium and selenoneine within the Arctic Ecosystems" (Director: G Massé; Co-directors: Lemire and Ayotte). 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. More samples were received recently (through DFO collaboration) and laboratory analyses are on-going. Dufour presented his preliminary findings at the RNUK meeting in Tasiujaq in November 2017 and at the Arctic Change conference in December 2017.

Nunavik country foods and lead

Can migratory birds become contaminated with lead during their migration out of Nunavik? A literature review to address concerns raised by Nunavimmiut.

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.

Chair MSc trainee student involved in this internship project: Cécile de Sérigny's project (2017) was entitled: "Can migratory birds become contaminated with lead during their migration outside Nunavik?: A literature review to address concerns raised by Nunavimmiut." (Director: Lemire, Co-directors: Ricard and Brisson at the NRBHSS). The literature review was completed in fall 2017. Findings were presented to the NNHC and will be publicised in Nunavik by the NRBHSS. Sérigny gave an oral presentation of her project at Arctic Change conference in December 2017. Sérigny is now working as a science teacher in a high school.

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 PhD student in this project: Cynthia Roy's project (2014-2018) is entitled: "Exposure to environmental contaminants and plasma metabolite profiles among the Inuit of Nunavik (Northern Quebec, Canada)" (Director: Ayotte, thesis committee: Lemire). She presented her preliminary findings at the 29th Annual Scientific Conference of the International Society for Environmental Epidemiology, Sydney, Australia. Targeted metabolomics data analyses are completed and statistical data of untargeted data are currently ongoing. A manuscript is in preparation to identify a metabolic signature associated with exposure to PCBs and MeHg. Moreover, the interactions between PCBs and n-polyunsaturated fatty acid and MeHg and Se will be evaluated to evaluate the effect of nutrients on the toxicity of contaminants on the metabolome. Those findings will help to elucidate the mechanisms by which contaminants operate and evaluate the need for preventive measures. Roy is expected to submit her thesis shortly. In January 2018, she started a position at the Laboratoire de sciences judiciaires et de médecine légale of the Quebec Government.

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 selenoneine status, MeHg exposure, and cardiometabolic outcomes and risk factors using data from Q2004 and Q2017. The objective of this project are 1) to determine sociodemographic, lifestyle, and dietary factors (including country foods) associated to selenoneine status in Nunavik adults that participated to Q2004; 2) 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 3) to analyze 13-year cohort data (303 participants, ≥ 31y) and new cross-sectional data (1327 youth and adult participants ≥ 16y) of Q2017.

Selenoneine and selenoproteins and metabolites of early diabetes were analysed in archived Q2004 samples. Statistical data analyses and four manuscripts are in preparation. Funding for selenoneine analysis in Q2017 participants was included in our 2018-2019 NCP proposal for Q2017 contaminant analysis.

Chair postdoctoral fellow in this project: Matthew Little's project (2017-2018) is entitled: "Country food selenoneine, mercury toxicity, and cardiometabolic diseases in Inuit populations in Nunavik" (Directors: Lemire and Ayotte). In 2017, Little received a Postdoctoral fellowship from CIHR and granted a position at the University of Guelph starting in fall 2018. Little attended the at the Northern Contaminants Program 25th Anniversary and Results Workshop in Yellowknife in September 2017, and the presented his preliminary findings at the NNHC meeting in Kuujjuaq in October 2017, the RNUK meeting in Tasiujaq in November 2017 and at the Arctic Change conference in December 2017.

Little will submit the manuscript on the determinants of selenoneine status (presented in the results section) to the NNHC and thereafter to Environment International for peer review in February 2018. From February through March 2018, Little will write a commentary (for submission in *Environment Health Perspectives*) on public health recommendations for selenium intake in Arctic populations. This commentary will identify existing gaps and outline characteristics of an effective public health strategy moving forward. Additionally, in February – May 2018, Matthew will investigate associations and linkages between MeHg exposure, nutrient intake, and early biomarkers of type 2 diabetes (T2D) and cardiovascular disease (CVD) risk factors, and will write another manuscript on this topic for submission by May 2018.

Objective 3: Zoonosis and other infectious agents

Prevalence, incidence and risk factors associated with exposure to Toxoplasma gondii, Trichinella nativa, Helicobacter pylori, Cryptosporidium spp. and the rabies virus in the Inuit population of Nunavik

In order to assess the possibility of developing immunity against rabies while manipulating potentially 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 to *T.gondii* while consuming raw fish.

A manuscript on communities' involvement and local knowledge during the 2013 trichinellosis outbreak in Inukjuak, Nunavik, is now in revision by the NRBHSS. A systematic review and meta-analysis about the exposure to *T.gondii* from raw or uncooked meat is also almost finalized.

Within the framework of Q2017, a PhD student is also responsible for studying five diseases and their protective and risk factors: two diseases transmitted by animals (toxoplasmosis and trichinellosis) and two diseases transmitted between humans (helicobacteriosis and cryptosporidiosis). Serology results for Q2017 participants will be available in starting in April 2018 and analysis for these infectious diseases preventive and risk factors will start shortly after.

Chair PhD student in this project: Julie Ducrocq's project (2015-2019) is entitled: "Global change, subsistence activities, and infectious diseases in Nunavik (Québec, Canada): Identifying protective and risk factors to foster Inuit health and traditions" (Director: Lemire; Co-directors: B Lévesque and G De Serres). In 2017, Ducrocq was granted a 3-year doctoral scholarship from the Fonds de recherche du Québec – Santé (FRQS). She was also selected for a Nasivvik Éric Dewailly scholarship in 2017, a field research scholarships from the Northern Scientific Training Program, 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 2017 laureate of the Mon projet nordique contest co-organized by the INQ and the Fonds de recherche du Québec. The laureates of this contest were invited to present their projects at the Arctic Circle Assembly held in Reykjavik, Iceland, in October 2017. Ducrocq also presented her preliminary findings at the Arctic Change conference in December 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, 2018-2020, $85K)

Within the framework of Q2017, additional funding was recently granted from Health Canada to include less persistent contaminants analysis in the Q2017 study. 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 NCP, and will be realized over the coming months 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 2017 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 sub-project

This multidisciplinary research sub-project is a component of the overarching GreenEdge project and 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 and consultations with the community members were held in August 2017. A NCP proposal was submitted Jan 10, 2018, to consult the Qikiqtarjuaq community members through the modelisation process and to eventually undertake a follow-up dietary and biomonitoring study in 2019.

Chair postdoctoral fellow in this project: Tiff-Annie Kenny's project (2017-2019) is entitled: "Qikiqtarjuaq Climate Change and Nutrition/Food Security Project" (Director: Lemire and Chan). Kenny led the NCP proposal writing and data analysis is on-going. Kenny presented her preliminary findings at the Arctic Change in December 2017 and at the GreenEdge meeting in Paris in February 2018. Kenny is also actually leading an innovative conceptual manuscript entitled: "Indigenous Peoples Food Systems & Environmental Change – An Equity an Environmental Justice Lens".

BriGHT project

BriGHT - Bridging Global change, Inuit Health and the Transforming Arctic Ocean (Co-PI: Lemire, Sentinelle Nord, 2017-2020: $933K)

This project aims to: 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 and the blood of Inuit (as part of Q2017) with respect to their food consumption profiles, the visual appearance of local marine foods, 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 local marine foods.

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 RNUK, the Nunavik hunters, fishermen and trapping association, for Arctic char sampling. Environmental samples analyses are on-going, and those in Q2017 samples will be started progressively next March 2018. Two MSc students and one postdoctoral fellow will be recruited for the health-related aspects of the BriGHT project in the coming months.

Objective 6: Knowledge mobilization

Knowledge integration

NQN project: Preliminary results were presented and discussed with the NNHC in June and October 2017, and January 2018.

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 the community level. The FNQLHSSC then invited Lemire and the project team to 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. 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 the 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 (PIs Lemire, Chan, Batal, Riva and Zhu). The full protocol will be sent to the Department of Indigenous Services Canada (DISC) in March 2018. The actual plan is that in fall 2018, regional consultations will be conducted to refine study objectives and design research tools and community mobilisation activities. The study recruitment is scheduled to start in April 2019, for a minimum of 8 years (1 year by province).

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 at that time, 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. During fall 2017, Yansouni replaced Riva as the Health Axis representative at McGill. Lemire attended the Second Northern Research Day at McGill in January 2018.

Manger notre Saint-Laurent – Réseau Québec Maritime (RQM): This new research proposal led by Lemire (acting PI) (co-PIs: Dumont, Plante and Lucas, co-I: Marquis, Wittman, Ayotte) was submitted to the RQM January 15, 2018. This innovative proposal aims at co-developing knowledge mobilisation e-tools and community interventions to promote marine foods from the Saint-Laurent River with several intersectoral partners. The project will be co-constructed in collaboration with three indigenous and non-indigenous communities from the Gaspésie, Madeleine-Islands and Baie des Chaleurs.

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.

Four 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 Islands and the Whales documentary was also presented at the Départment de médecine sociale et préventive of the Université Laval on October 5, 2017.

The second Nasivvik Chair Éric Dewailly pour des projets communautaires en santé autochtone scholarships was granted in 2017 to Caroline Moisan (5K) for her project entitled Coming back to communities: considering attitudes toward early pregnancy and to Julie Ducrocq (2.4K) for her project entitled: Elaboration collaborative et participative d'un guide sur les maladies animals et zoonotiques pour les Inuit du Nunavik.

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 entitled 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 in August 2017 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 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) 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 (Nasivvik Chair and PFSN scholarships) in collaboration with the NRBHSS and the NRC. In November 2018, Ducrocq attended the RNUK meeting and visited the NRC to consult Inuit partners and build a collection of pictures of pathologies to build the collaborative guidebook which will help 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 2017 summer research internship in the Chair's team, completed a literature review to build a top 20 of "must-read" recent scientific papers about Inuit health in order to increase knowledge translation to clinicians and public health practitioners.

This collaborative project was realized in collaboration with Glenda Sandy (Naskapi nurse and MSc student in community health), Dr. Ouellet and Dr Cauchon (Dept. Family Medicine), Dr. Fortin (MD in Nunavik) and Christopher Fletcher. This project consisted of reading, selecting and summarizing a top 20 of recent scientific papers about Inuit health that could influence the practice of clinicians and other health practitioners in Nunavik for the following objectives: (i) To increase knowledge translation among 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. Once a month (starting in March 2018), a newsletter summarizing a selection of these 20 papers will be sent by email to Nunavik health practitioners and posted on the Facebook page of the Nasivvik Chair. The list of the top 20 is available on the Nasivvik Chair website.

Next March 21, 2018, Lemire will co-facilitate with Dr Poitras, dean of the Faculty of Medicine at Université Laval, a panel entitled: "La recherche et les stages en santé mondiale: la réalité du terrain" during the 2018 Global Health meeting at Université Laval, which will feature three graduate students in Global Health (including the Nasivvik Chair intern Vincent Paquin) as well as key players in participatory research: G Muckle (Social Science vice-dean of studies), JS Moore (Biology) and M Alary (Global Health).

A book entitled Our Sea, Our Health, co-authored by Rapinski, Cuerrier, Harris, Lemire and the elders of Kangiqsujuaq and Ivujivik, will be published shortly by the Avataq Cultural Institute in English, French and Inuktitut. This book aims to share knowledge about local marine foods and related-health properties with Inuit community members and is based on the manuscript entitled: Inuit perception of marine organisms: from folk classification to food harvest (see publication list). This research project was funded by our previous ArcticNet grant (2012-2015).

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 reflects the most up-to-date clinical algorithms on these two contaminants in the country and is adapted to the indigenous context. These two documents will be used in other projects like the FENHCY.

"Elevated exposure to Hg and Pb is a public health priority in Nunavik" (Dr. Bouchard, Congrès Nordique 2017). NQN and Q2017 project findings will support the planning of future preventive interventions by the NRBHSS.

Lemire's presentations of JES!-YEH! project findings to the FNQLHSSC, AFN and the FNIHB at federal and provincial levels raised awareness about the issues of anemia, obesity and diabetes among First Nation children, and particularly among teenagers, for which few data are available. The nutritionists at the FNQLHSSC and FNIHB are currently building community tools for local action plans. Recent project findings will be presented to community members and at UQAT in Val d'Or in March 2018 and the FNQLHSSC in spring 2018.

National and international councils and expert panels

In April 2017, Lemire participated in the 2-day annual meeting of HHAG-AMAP and presented at the subsequent AMAP conference in Virginia, US. A great concern/challenge discussed with circumpolar experts was the high prevalence of elevated Hg exposure in Nunavik and importance of considering seasonality of Hg exposure when assessing Hg exposure. The importance of considering and emphasizing 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.

Lemire and Ayotte will host the next 48th HHAG-AMAP meeting in Quebec City on Feb 27 - March 1st. A public evening is organized for March 1st so that colleagues and graduate students will have the chance to meet with AMAP delegates and NRBHSS practitioners. During this evening, we will present the documentary The Islands and the Whales, featuring Pal Weihe, an AMAP delegate from the Faroese Islands.

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 entered 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 ongoing chair 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 under 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 (CHMS, 2013).

Similarly, almost all older and new POPs were not detected and/or lower than CHMS except three contaminants. Plasma PNFA level, a more recent perfluorinated compound, was high in some communities, and particularly high among children of 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, were very low. PNFA levels were considerably higher than in CHMS, and among Nunavik pregnant women in 2017 (see next section) and 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 today, no local source have been identified. Environmental investigations are 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". Finally, bisphenol A and monobenzyle phtalate levels in urine were slightly more elevated than CHMS (Cycle 2), particularly among study participants aged 6 to 19 years old (CHMS, 2013).

Nutritional and health status

As shown in Table 1, 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) (Copper et al., 2012). According to WHO (2011), anemia prevalence above 20% represents a moderate public health problem. 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 known to interact with other metals with similar valence such cadmium (Cd), cobalt (Co), manganese (Mn), lead (Pb) and zinc (Zn) (Flanagan et al., 1980). Pb and Cd are xenobiotic and, in indigenous context, often related to Pb-ammunition use and smoking. Conversely, Mn, Zn, and Co are dietary nutrients that are essential for the metabolism of lipids, proteins, and carbohydrates, and generally found in high concentrations in the diet (IOM, 2006). All these metals share common absorptive pathways with iron, and ID is known to trigger their up-regulation, thereby increasing their intestinal absorption, concentration inside the body, and possibly, their toxicity (Flanagan et al, 1980).

In the present study, blood Mn and Co levels were higher than in CHMS (Cycle 2) (CHMS, 2013). Blood Mn levels were found to be elevated in 12% of participants, which presented blood levels above 20 µg/L, the former Quebec MADO level for Mn. Conversely, hair Mn levels were low and no environmental sources of manganese were found. Like for ID, no difference in blood Mn was found between the two study regions. As shown in Figure 1, serum ferritin, an indicator of iron status, and blood Mn were strongly negatively correlated, supporting the hypothesis that the more iron deficient the organism is, the higher blood Mn levels are. This was likewise the case for blood Co.

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 (27% and 41% respectively), and particularly among those aged 12 to 19 years old and from the Innu communities. Overweight and obesity prevalence was between two and five times higher than in CHMS for the same age and sex

Table 1. Proportions of ID and anemia and blood divalent metal concentrations for the JES!-YEH! study participants by nation.

Variables	**Anishinaabe (n=107)**		**Innu (n=86)**	
	% (95%CI)	**Geometric means (95% CI)**	**% (95%CI)**	**Geometric means (95% CI)**
Age /years‡		9.75 (8.84 - 10.66)		10.63 (9.62 - 11.62)
3 to 5 yrs 6 to 11 yrs 12 to 19 yrs	20.6 (14.0 - 29.2) 42.1 (33.1 - 51.5) 37.4 (28.8 - 46.8)		15.1 (9.0 - 24) 38.4 (28.8 - 48.9) 46.5 (36.4 - 57.0)	
Girls	48.6 (39.3 – 58.0)		46.5 (36.4 - 57)	
Serum ferritin (µg/L)		25.97 (22.76 - 29.63)		30.85 (26.03 - 3 .56)
ID	20.6 (14.0 - 29.2)		21.2 (13.8 - 31.0)	
ID (age group & sex) 3 to 5 yrs 6 to 11 yrs girls 6 to 11 yrs boys 12 to 19 yrs girls 12 to 19 yrs boys	 22.7 (10.1 - 43.4) 4.8 (0.9 - 22.7) 4.2 (0.7 - 20.2) 52.4 (32.4 - 71.7) 21.1 (0.9, - 43.3)		 0.0 (0.0 - 24) 14.3 (4.0 - 39.9) * 31.6 (15.4 - 54.0) * 38.1 (20.8 - 59.1) 10.5 (29.0 - 31.3)	
Hemoglobin (g/L)		124.56 (121.90 - 127.27)		125.06 (121.67 - 128.54)
Anemia	16.8 (10.9 - 25.0)		18.8 (11.9 - 28.4)	
Anemia(age group & sex) 3 to 5 yrs 6 to 11 yrs girls 6 to 11 yrs boys 12 to 19 yrs girls 12 to 19 yrs boys	 4.6 (0.08 - 21.8) 14.3 (5.0 - 34.5) 12.5 (4.3 - 31.0) 33.3 (17.2 - 54.6) 21.1 (8.5 - 43)		 8.3 (14.9 - 35.4) 21.4 (7.6 - 47.6) 31.6 (15.4 - 54.0) 19.1 (7.7 - 40.0) 10.5 (2.9 - 31.4)	
Blood Cd (µg/L)		0.16 (0.13 - 0.19)		0.20 * (0.14 - 0.28)
Blood Co (µg/L)		0.25 * (0.24 - 0.27)		0.19 (0.17 - 0.20)
Blood Mn (µg/L)		15.52 (14.80 - 16.28)		15.38 (14.57 - 16.25)
Blood Pb (µg/L)		5.55 (5.05 - 6.10)		6.41 (5.74 - 7.16)
Serum Zn (µg/L)		18.40 (17.89 - 18.93)		17.89 (17.30 - 18.49)

*Significantly higher in this nation ($P<0.05$), ‡arithmetic means

groups (Roberts et al., 2012). A high prevalence of elevated waist-to-height ratio, an indicator central obesity and cardiometabolic risk, was also found to be very high: 99% and 66% of participants presented abdominal obesity in the innu and anishinabe communities respectively. Moreover, few participants from the innu communities were found with elevated glycated haemoglobin and random glucose levels possibly associated to diabetes, of which 2 were newly identified Type 2 potential cases.

Health determinants

One-third (35%) of participants from the Anishinaabe communities reported to live in overcrowded dwellings (more than 1 person per room), which is higher than other First Nation communities in Canada (27%), and non-Indigenous population living in Canadian cities (4%) (Statistics Canada, 2011). Moreover, up to 43% of participants from these communities lived in households suffering from food insecurity, compared to 8% in non-First Nations Canadian households (Statistics Canada, 2015). Food consumption data

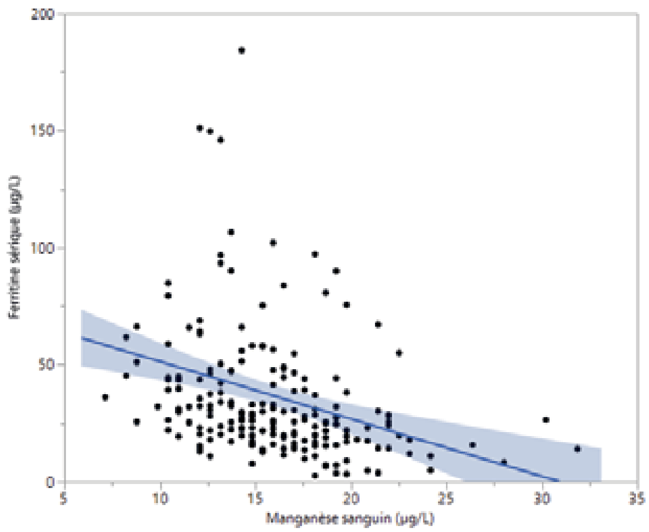

Figure 1. Association between serum ferritin and blood Mn in JES!-YEH! (Spearman ρ = - 0.42, p < 0.0001).

highlight that traditional foods seemed to be relatively little consumed in general, while ultra-processed foods such as processed meats (eg. sausages and other cold meats), sweets, junk food (eg. chips, pastries, poutine) and powdered juices were more frequently.

Pregnant women and adults in Nunavik: Project NQN

During Year 1 (2016-2017), a total of 97 pregnant women from 13 communities in Nunavik were recruited for biomonitoring activities in October-December 2016 (n=6) and January-March 2017 (n=91). Biomonitoring results show that up to 23% of participants had blood Hg levels above the Health Canada guideline (≥ 8 µg/L), and among these, few participants were 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% MeHg. Moreover, a few participants still had blood lead (Pb) above the most recent level of concern (≥ 50 µg/L). Up to 60% of participants presented iron deficiency and 39% had anemia, among which almost all (30% over 39%) were classified with iron deficiency anemia (Lemire et al., NCP synopsis 2017).

Most recent data sequential hair Hg analyses show important monthly variations in Hg exposure, from 0.1 to 23.1 µg/g. Temporal profiles in hair Hg seem to be more comparable among participants from specific communities, with one or two peaks in exposure at

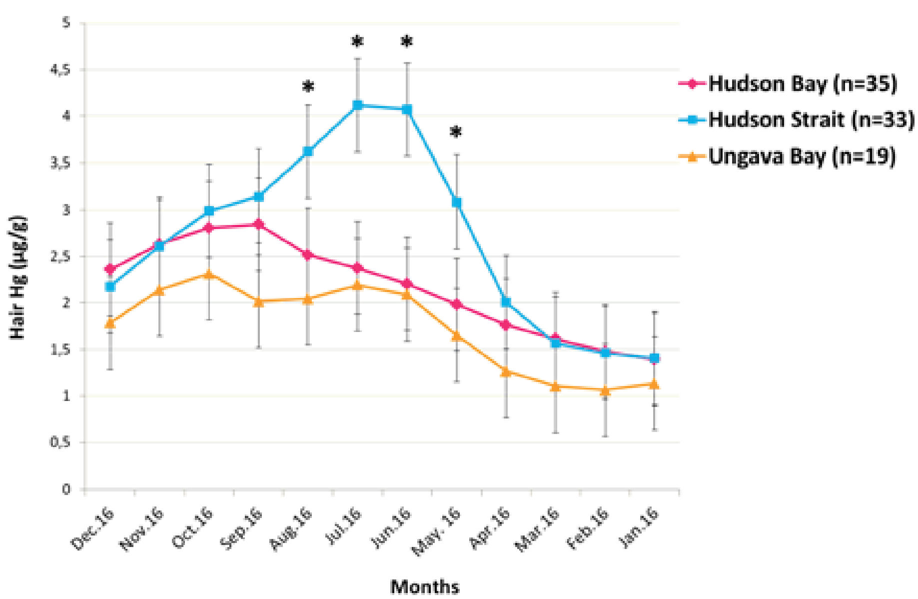

Figure 2. Average monthly and regional hair Hg exposure among pregnant women in Nunavik in 2016.

different period of the year. As shown in Figure 2, Hg exposure was greatly lower and not different between Nunavik regions during winter months (January – April 2016), whereas Hg exposure was significantly higher in the summer months (May and August 2016), but primarily in the Hudson Strait villages. Interestingly, in the Qanuippitaa? survey (conducted in August-September 2004), women of childbearing age from the Hudson Strait region had significantly higher blood Hg, blood Se and red blood cells (RBC) omega-3 fatty acids (Lemire, Kwan et al. 2015). Conversely, at testing time in 2016-2017 (primarily January – March 2017), pregnant women blood Hg exposure and blood Se status was not statistically significant between regions and RBC omega-3 fatty acids were significantly lower in the Hudson Strait villages, which was contrary than observed in the Q2004 survey.

Since the present biomonitoring study was primarily conducted in January – March 2016, these latest findings highlight that pregnant women blood Hg exposure was most probably underestimated in 2016-2017 (23% above Hg Health Canada guideline (≥ 8 μg/L)). The good news is that the Q2017 survey was conducted between August and October 2017. Future pregnant women biomonitoring activities in Nunavik should therefore focus on recruiting participants in late summer and early fall.

Table 2 show pregnant women average exposure levels to legacy POPs, new POPS, some CECs, Hg, Pb, Se and polyunsaturated fatty acids (PUFAs) ratio (n-3/n-6) in 2016-2017 as well as percentage of change since the last 2012-2013 pregnant women biomonitoring study in Nunavik and since each contaminant was first measured in Nunavik. Overall, all contaminants and nutrient measured decreased markedly since they were first measured (1992, 2004 and 2007), except the most recent perfluorinated compounds (PFCs) such as perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA) and perfluoroundecanoic acid (PFUDA) which have increased since the latest biomonitoring study in Nunavik. For instance, PFNA levels were higher than those reported for adults in the Canadian Health Measures Survey (Cycle 2, 2009-2011) (0.82 μg/L (95%CI: 0.39 – 1.9 μg/L) (CHMS, 2013). It is to note that in 2016 the Government of Canada has amended the Canada's Prohibition of Certain Toxic Substances Regulations to add long-chain PFCs including PFNA (ECCC, 2017) but since these substances are persistent, exposure levels in Nunavik may not decrease rapidly.

As shown in Table 3 below, whereas most pregnant women (≥ 78%) were aware that eating country food was good for health and a good source of healthy fats, only one third (36%) had heard the public messages about beluga meat to prevent acute Hg exposure and even fewer (16%) were aware of the importance of avoiding lead shot (pellets) when hunting to prevent Pb exposure.

These results are being used by the Regional Health Authority in their rationale for proposed sub-regional communication/knowledge mobilization meetings this coming year from the NCP to discuss Hg and Pb communication strategies in the region.

Nunavik country foods and selenoneine

Selenoneine, an organic form of selenium, was found to represent more than 50% of total Se 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 (Y Yamashita et al. 2013). Our most recent data also show relatively high concentrations of total Se in the two marine food chains of interest (pelagic and benthic), especially in marine mammal muscle and liver tissues, along with large concentrations of polyunsaturated fatty acids, particularly for zooplankton. Walrus muscle exhibited the highest selenoneine concentrations, which in average represented 9% of total Se, and in one case reached up to 46% of total Se. The total Se average content of walrus muscle was comparable to the levels found in beluga mattaaq (2.5 to 6.0 μg/g in wet weight), although the selenoneine proportion in walrus is about 5 times lower than in beluga mattaaq (Table 4).

Table 2. Nunavik pregnant women exposure to legacy POPs, new POPS, some CECs, Hg, Pb, Se and polyunsaturated fatty acids (PUFAs) in 2016-2017 and time-trends since 2012-2013 and each contaminant was first measured in Nunavik.

PCBs and OCs (plasma. µg/kg lipids)	2017 Geometric Mean	% change between 2012-2013 and 2017	% change since 1992
Oxychlordane	16	-26.90%	-79.33%
Transnonachlor	32	-24.24%	-72.44%
P'P DDE	97	-25.90%	-85.01%
P'P DDT	40% <LOD		
PCB 118	5	-24.09%	-82.56%
PCB 138	14	-26.01%	-87.81%
PCB 153	29	-28.51%	-83.43%
PCB 180	29	-28.51%	-83.43%
PCB 183	2	-19.35%	-86.60%
Hexachlorobenzene	18	-11.44%	-81.34%
Aroclor 1260	226	-27.59%	-85.22%
ß-HCH	2.1	-15.51%	-83.37%
Mirex	2.7	-10.89%	-79.45%
cis-Nonachlor	4.5	-25.17%	-84.23%
Metals and PUFAs (blood. µg/L; RBC. ratio)	2017 Geometric Mean	% change between 2012-2013 and 2017	% change since 1992
Hg	4.2	-18.07%	-66.21%
Pb	12	-15.45%	-71.62%
Se	232	-25.15%	-40.08%
PUFAs N3/N6	0.39	-12.43%	-74.61%
PBDEs. PCP. PFCs (plasma. µg/kg lipids)	2017 Geometric Mean	% change between 2012-2013 and 2017	% change since 2004
PBDE 47	40% <LOD		
PBDE 153	40% <LOD		
Pentachlorophenol	0.16	-46.53%	-70.85%
PFOS	3.3	-14.03%	-64.89%
Older PFCs (plasma. µg/kg lipids)	2017 Geometric Mean	% change between 2012-2013 and 2017	% change since 2007
PFOA	0.55	-23.68%	-30.70%
PFHXS	0.26	-27.56%	-39.24%
More recent PFCs (plasma. µg/kg lipids)	2017 Geometric Mean	% change between 2012-2013 and 2017	
PFNA	2.4	+ 14.88%	
PFDA	0.52	+ 7.43%	
PFUDA	0.59	+ 12.87%	

Table 3. Percentage of awareness of about health messages among pregnant women that participated in the project (n=97).

Advice 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 4. Total Se and selenoneine concentrations (reported per grams of carbon and grams of wet weight) in marine organisms from pelagic and benthic food chains in the Arctic.

Species (n total Se, n selenoneine)		Total Se		Selenoneine		% Selenoneine
		µg/g C GM (range)	µg/g WW GM (range)	µg/g C GM (range)	µg/g WW GM (range)	% GM (range)
Phytoplankton (6,1)		5.96 (4.04 – 9.75)	0.05 (0.02 – 0.07)	< LOD	< LOD	N/A
Ice algae (4, 4)		2.47 (1.37 – 6.47)	0.03 (0.01 – 0.05)	< LOD	< LOD	N/A
Zooplankton	1000um+ (7, 7)	5.08 (2.83 – 6.52)	0.26 (0.22 – 0.32)	0.44 (0.27 – 0.69)	0.02 (0.01 – 0.03)	8.55 (5.16 – 13.28)
	Calanus spp (2, 2)	4.60 (3.97 – 5.33)	0.18 (0.16 – 0.21)	0.40 (0.25 – 0.63)	0.02 (0.01 – 0.02)	8.60 (6.25 – 11.82)
Clams	*Mya truncata* (29, 29)	7.18 (5.00 – 12.11)	0.40 (0.27 – 0.97)	0.78 (0.24 – 1.61)	0.05 (0.02 – 0.10)	10.99 (4.35 – 25.42)
	Serripes groenlandicus (28, 28)	6.57 (5.01 – 10.15)	0.39 (0.29 – 0.54)	0.503 (0.19 – 1.83)	0.03 (0.01 – 0.11)	7.69 (2.30 – 25.71)
Arctic cod (13,7)		3.29 (2.76 – 3.81)	0.31 (0.24 – 0.39)	0.14 (0.08 – 0.23)	0.01 (0.01 – 0.02)	4.28 (2.90 – 6.74)
Sculpin (11, 5)		3.95 (2.98 – 5.93)	0.32 (0.25 – 0.55)	< LOD	< LOD	N/A
Walrus	Muscle (16, 16)	11.46 (2.99 – 73.12)	1.41 (0.38 – 8.84)	1.07 (0.12 – 3.59)	0.13 (0.02 – 0.45)	9.37 (1.26 – 45.95)
Seal	Muscle (3, 13)	2.57 (2.03 – 3.21)	0.38 (0.28 – 0.50)	0.12 (0.02 – 0.52)	0.02 (0.00 – 0.05)	4.80 (0.70 – 16.12)
	Liver (3, 13)	30.93 (7.72 – 89.75)	5.09 (1.14 – 13.88)	0.39 (0.25 – 0.92)	0.05 (0.03 – 0.14)	1.27 (0.60 – 3.37)
Seaweeds (4,6)		1.01 (0.39 – 1.76)	0.05 (0.03 – 0.09)	0.08 (0.00 – 0.28)	0.01 (0.00 – 0.02)	7.33 (2.57 – 73.27)

Through stable isotope analysis, we have been able to identify the two basal carbon signatures of the primary production pools and their relative inputs in the higher trophic levels (Figure 3). It is a useful tool to quantify the proportions of different food sources to the primary consumers diets. The results shows, amongst others, that the benthic bivalves *Mya truncata* and *Serripes groenlandicus* are strongly associated with the rapid sinking of ice algae during the ice melting season.

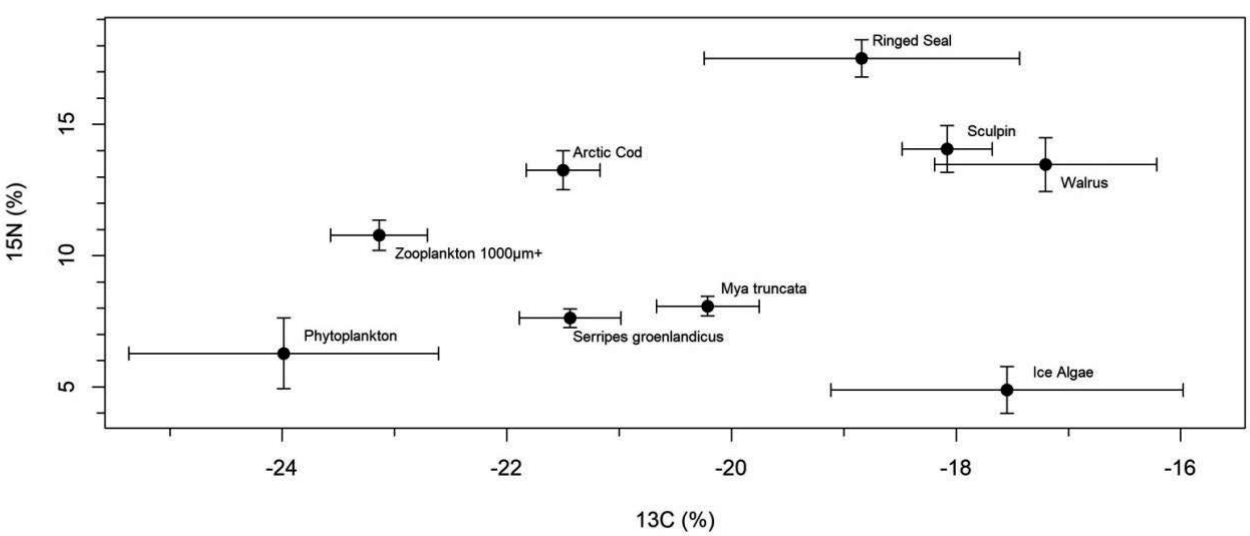

Figure 3. Basal carbon signatures of marine organisms from pelagic and benthic food chain in the Arctic.

Nunavik country foods and lead: Can migratory birds become contaminated with lead during their migration out of Nunavik? A literature review to address concerns raised by Nunavimmiut.

This literature review identified snow geese, Canadian geese and common eiders as the main species consumed by the Inuit in Nunavik for their flesh and eggs. Lead (Pb) pellets are still used for hunting in some regions of geese migration territories, including James Bay, Newfoundland and various American ranges (Table 5). 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 pellets have been banned only since 2014.

Both geese and eiders can be contaminated with Pb pellets 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.

In summary, migratory birds can be contaminated by Pb during the accidental ingestion of Pb pellets instead of gravel gizzard during their migration outside Nunavik, but more importantly, migratory birds can also be contaminated within Nunavik through the persistent use of Pb pellets and contamination of the local environment (Figure 4). The Pb concentrations in the flesh migratory birds resulting from the ingestion of Pb pellets left in the environment has not been extensively studied. Still, the importance of Pb contamination appears negligible compared to the contamination of migratory bird flesh caused by the direct use Pb ammunition for hunting, and the related ingestion of Pb shots or fragments of Pb remaining in the flesh (even after cleaning the animal) as a result of hunting with Pb ammunition.

These results also highlight that use of Pb-free ammunitions is the primary measure to protect Nunavimmiut from Pb exposure, and particularly young children which are more sensitive to Pb neurotoxicity. This project supports the communication campaign and other measures planned to be implemented by the NRBHSS to prevent exposure of Nunavimmiut to Pb.

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 PCB-153 and blood MeHg levels were positively associated with plasma concentrations of several amino acids (AAs) and acylcarnitines (ACs) (Figure 5). Statistical analyses for metabolites identified through untargeted metabolomics are also ongoing.

Table 5. Summary of Pb pellets legislation by countries of migration territories.

	Canada	Greenland	United States
Migratory birds hunting	Pb pellets banned since 1999 Still used by some indigenous groups	Pb pellets banned since 2004	Pb pellets banned since 1991
Other Pb shots uses	Other hunting activities like for terrestrial birds and big game Shooting range	Not used anymore: forbidden to import, sell, own and use Pb pellets	Other hunting activities* Shooting range (6000 sites)

* Legislation varies between US States.

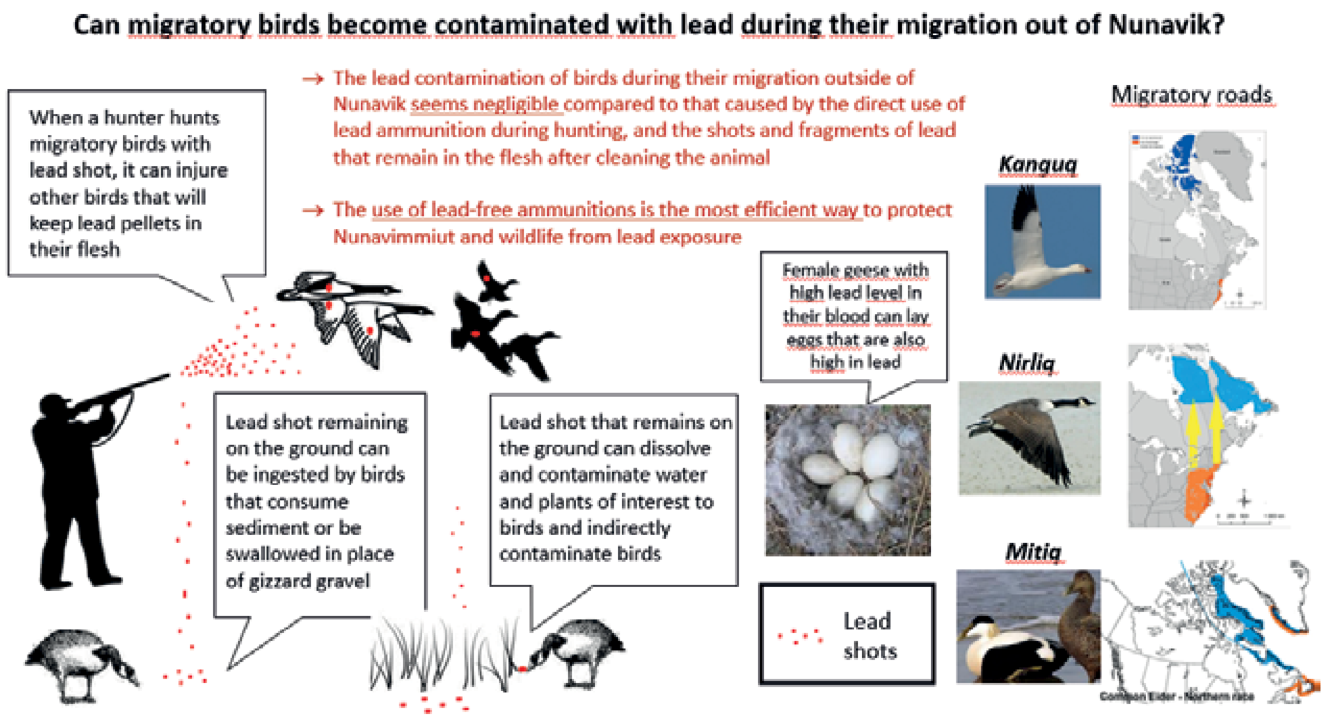

Figure 4. Summary of the results of the present litterature review and prepared for the eventual future communication campaign planned to be implemented by the NRBHSS.

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

In Q2004 archived samples, selenoneine was found in all red blood cells (RBC) (range: 1 µg/L to 3226 µg/L), and accounted for a large proportion of total Se in RBCs (geometric mean: 26%; although values reached up to 92%) (Table 6). RBC Se and RBC selenoneine concentrations were higher among women ($p<0.001$), while plasma Se concentrations were higher among men ($p<0.001$). RBC selenoneine concentrations were considerably higher ($p<0.001$) in Hudson Strait communities (age-adjusted geometric mean (range)

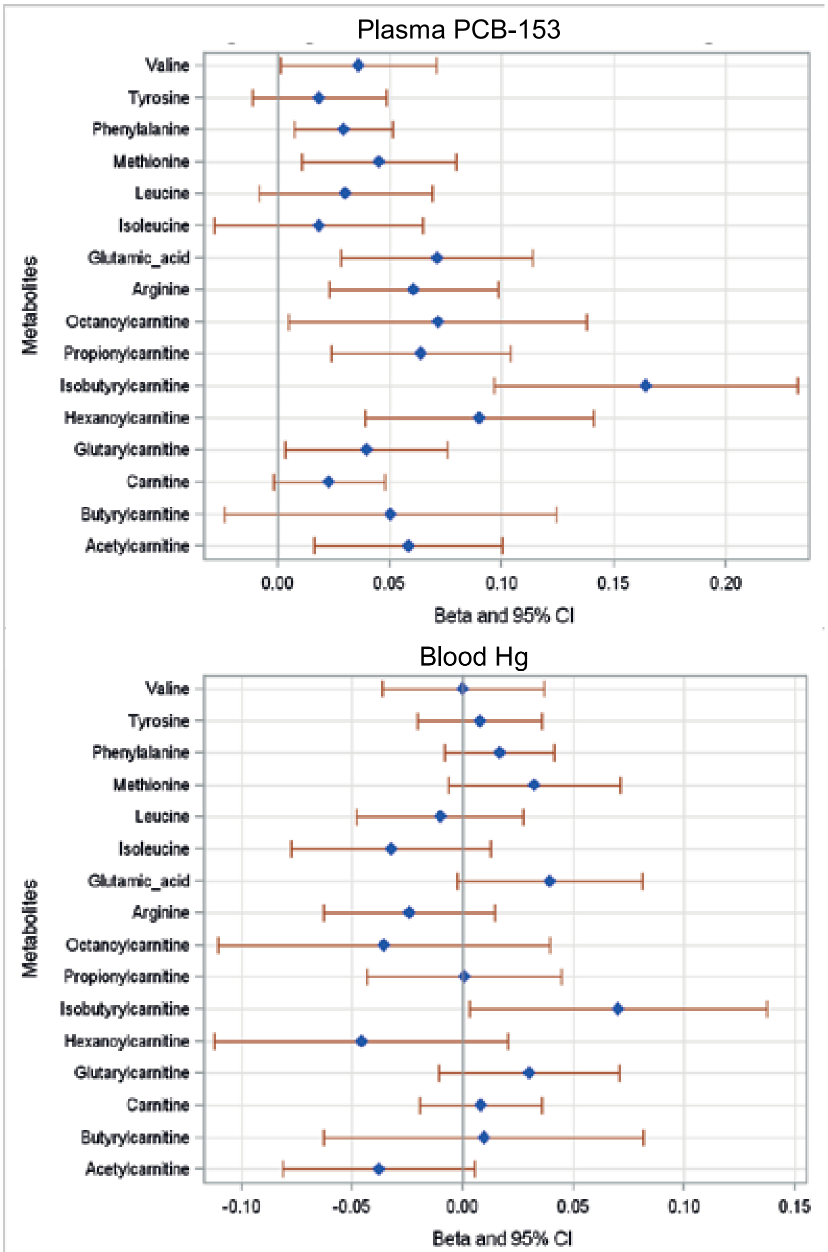

Figure 5. Beta estimate and 95 % confidence interval for the 16 targeted metabolites significantly associated to plasma PCBs or blood Hg levels.

for men: 241 µg/L (3 – 3226 µg/L); women: 426.3 (7 – 2708 µg/L)) when compared to communities in Hudson Bay (men: 60.9 µg/L (1 – 1780 µg/L); women: 102.6 (5 – 1409 µg/L)) and Ungava Bay (men: 67 µg/L (53 – 84 µg/L); women: 117.8 (95-145 µg/L)).

RBC selenoneine was highly correlated with RBC Se (rs=0.96, p<0.001) and whole blood Se (rs=0.89, p<0.001) but only weakly correlated with plasma Se (rs=0.13, p<0.001). The RBC selenoneine/RBC Se ratio was positively correlated with RBC Se (rs=0.82;

Table 6. Summary statistics of blood compounds among participants of the Qanuippitaa? 2004 study.

Variables	N	Geometric Means			p-value*
		Men	Women	Overall (range)	
Se compounds	885				
Total Se – whole blood (µg/L)		283.3	301.5	293.1 (118.5-3555)	0.039
Total Se – RBCs (µg/L)		502.8	609.4	561.6 (174.7-3892.6)	<0.001
Total selenoneine – RBCs (µg Se/L)		87.6	150.3	118.0 (0.99-3226.3)	<0.001
Methylated selenoneine – RBCs (µg Se/L)		5.5	7.3	6.4 (1.97-124.28)	<0.001
RBC selenoneine:RBC Se ratio		0.21	0.32	0.26 (0.003 – 0.92)	<0.001
Total Se – plasma	858	144.2	135.8	139.6 (87.4-228.8)	<0.001
GpX3† (µg/L)		35.9	34.4	34.9 (19.6-77.5)	<0.001
SePP (µg/L)		75.2	69.2	71.18 (45.9-109.7)	<0.001
SeAlb (µg/L)		32.5	31.6	32.0 (19.2-75.6)	0.065

*p-value represents one-way analyses of variance for comparison of means between men and women following log-transformation of variables; †GPx3 and unretained small molecules containing Se

p<0.001), indicating that in the study population, as RBC Se rises, an increasing proportion of Se is found as selenoneine. RBC selenoneine was also highly correlated with whole blood Hg (rs=0.66; p<0.001) and MeHg (rs=0.66; p<0.001).

Several sociodemographic, lifestyle, and dietary factors were associated with RBC selenoneine. Increased age, higher body-mass index (BMI), and female sex were positively associated with RBC selenoneine. Beluga mattaaq consumption was the only country food variable positively associated with RBC selenoneine and RBC Se, but was not associated with plasma Se (Figure 6). Individuals from the Hudson Strait had significantly higher RBC selenoneine concentrations than individuals from Hudson Bay and Ungava Bay. Finally, consumption of market meats was negatively associated with RBC selenoneine.

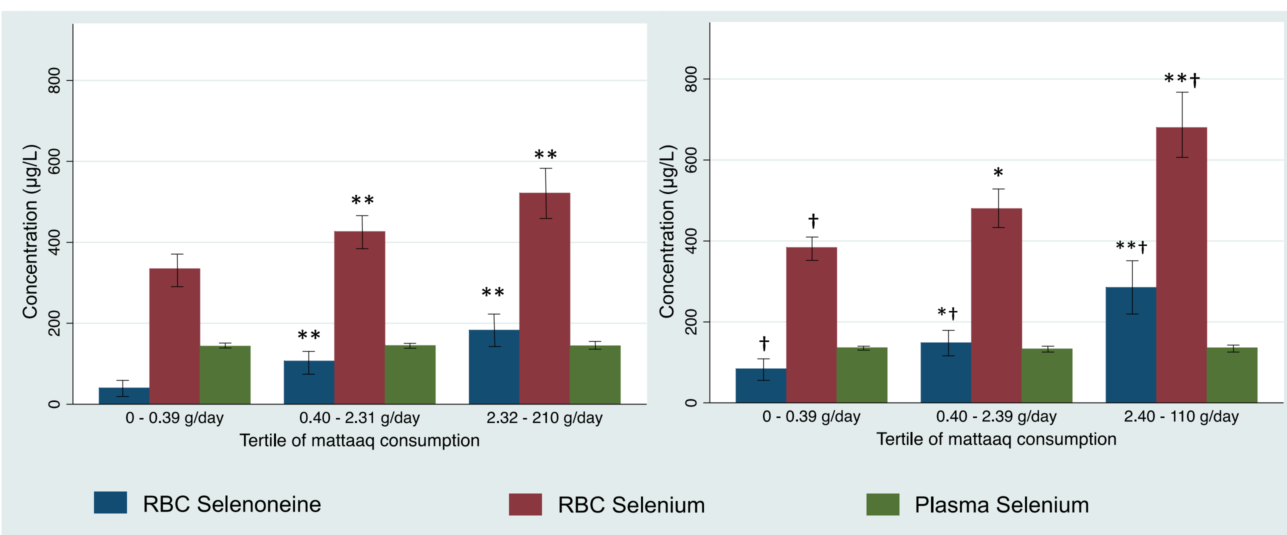

*Figure 6. Geometric means of RBC selenoneine, RBC Se, and plasma Se concentrations by tertile of beluga mattaaq consumption stratified by men (left) and women (right). Note: Wilcox rank-sum test used to determine significant differences between categories; *p-value<0.01 compared to sex-specific lowest tertile; **p-value<0.001 compared to sex-specific lowest tertile; †significantly different at p-value<0.05 compared to tertile-matched men.*

Objective 3: Zoonosis and other infectious agents

Prevalence, incidence and risk factors associated with exposure to Toxoplasma gondii, Trichinella nativa, Helicobacter pylori, Cryptosporidium spp. and the rabies virus in the Inuit population of Nunavik

Rabies

Only two of the 198 Q2004 individuals tested for rabies antibodies demonstrated antibody levels superior to 0.5 UI/ml. All others samples had undetectable levels (under the 0.06 UI/ml minimal detection threshold). For both seropositive individuals, a medical file review and a phone interview revealed that rabies vaccination was received prior to the 2004 Inuit Health Survey while this information was not concealed in the 1991 – 2004 Nunavik rabies prophylaxis registry. A manuscript is in preparation.

Toxoplasma gondii in fish

T. gondii was found in about 10% of submitted fish tissues from Nunavik by molecular methods which led the NRBHSS to modify their dietary recommendations for pregnant Inuit women. Further characterization of the risk related to consuming raw fish is needed and the organization of a sampling project for whole fish is in discussion with the Nunavik Research Center and Health Canada.

Systematic review and meta-analysis about the exposure to T. gondii from raw or uncooked meat

The systematic and meta-analysis preliminary results suggest that eating raw or undercooked meat increases the risk of being exposed to *T. gondii*. The pooled adjusted odds ratio was 1.84 (1.61 – 2.11; 95% CI). Advanced meta-regression analysis is underway and results should be available in April 2018. The manuscript is almost finalised.

Trichinella nativa outbreak

The creation of a unique, intersectoral and culturally appropriate local advisory group composed of four community members (hunter, communication officer, social worker and local nurse) fostered the use of local knowledge to understand all aspects of the modern food system in Inukjuak. Sharing of scientific and local ways of knowing was critical for the management of this *Trichinella nativa* outbreak and contributed to community members' mobilization and empowerment with respect to local food safety issues. The manuscript is currently in revision by the NRBHSS.

Objective 5: Impact of climate and ecosystem changes on local food systems

GreenEdge – Food Security and Human Health Project sub-project

Territorial Health Meeting - Iqaluit, Nunavut

A meeting was held at the Nunavut Research Institute (Iqaluit, NU) on August 30th 2017 to convene human health researchers (Lemire, Chan and Kenny) and key representatives from the Nunavut Department of Health, and Nunavut Tungavik Inc. The objectives of this meeting were to: i. Update on epidemiological findings from the 2007 - 2008 Inuit Health Survey; ii. Discuss on-going collaboration on risk-benefit assessments of country foods; and, iii. Present a newly proposed study examining climate change and food security in Qikiqtarjuaq (NU).

Community Consultation - Qikiqtarjuaq, Nunavut

A community consultation was held at the Municipal Hall (Hamlet of Qikiqtarjuaq) in Qikiqtarjuaq (NU) on August 31st 2017. The consultation was co-organized with the Community Health Representative and was held as a community feast and open community meeting (English with Inuktitut interpreter). The objectives of this initial community consultation were to: i. Present the proposed project which aims to investigate the impact of climate change on Arctic marine environments and local food security, and solicit community interest and feedback; ii. To discuss the changing dynamics of marine environments and the impacts on country food harvest, food security, and human health. Approximately 40 people, including representatives from the Hamlet of Qikiqtarjuaq, the Community Wellness Centre, the Health Centre, the Nattivak Hunters' & Trappers' Organization and the Government of Nunavut (Department of Environment) were in attendance.

Progress on ecosystem and dietary/health modelling for the GreenEdge project

As this study builds on three previous diet, nutrition and contaminants research projects (i. the 1987-88 Broughton Island Study; ii. the 1998-99 McGill University Centre for Indigenous Nutrition and Environment (CINE) study; iii. the 2007-08 Inuit Health Survey (IHS)) we have recoded and harmonized the databases and completed preliminary studies to confirm that the three datasets are indeed comparable. The IHS data are only available to the research team at the regional level (Qikiqtaaluk Region). With support from the community, we are applying for access to community specific data for Qikiqtarjuaq from the 2007-8 IHS through the National Inuit Health Survey Working Group (Nunavut). Meanwhile, based on in situ data gathered during the GreenEdge ice camp and sea campaign, our collaborators (St. Béat and Maps), have developed regional planktonic food web models of Baffin Bay, which integrate several biotic (from bacteria to arctic cod larvae through primary producers and several groups of zooplankton), and abiotic (e.g. particulate and dissolved organic carbon) compartments. These food web models are foundational to higher order ecosystem models that will be used to assess climate change impacts on food security (2018-2019). We have also developed a collaboration with marine ecosystem modellers at the Institute for the Oceans and Fisheries at the University of British Columbia to develop an integrated modelling framework for coastal socioecological systems. This is part of a broader network of researchers and case studies investigating the impact of climate change on oceans and coastal communities across Canada.

Development of a conceptual framework for the analysis of mixed food systems in the face of global changes (Kenny et al, Indigenous Peoples Food Systems & Environmental Change – An Equity an Environmental Justice Lens, in preparation)

Environmental and sociopolitical forces are increasingly disrupting opportunities for Indigenous communities around the world to rely on traditional food systems for health and well-being (Simpson, 2003). These include climate change, industrial activities (e.g. mining, deforestation, hydroelectric development), environmental contaminants, land and resource management systems and governance frameworks (Herrmann et al., 2014; Hoover, 2013). Degraded ecosystems undermine the food security and food sovereignty of Indigenous communities by limiting local control over the quality, safety, and acceptability of local foods, and by increasing dependency on global food systems (Loring & Gerlach, 2009). Accordingly, the health risks faced by Indigenous Peoples cannot be divorced from the various environmental and sociopolitical forces that disrupt traditional food systems by eroding the integrity of their territories, resources, economic and social systems, as well as their institutions, autonomy, local knowledge, and 'collective-capacity' (Damman, Eide, & Kuhnlein, 2008; Whyte, 2017). Systems-based frameworks are thus needed to examine the interactions between global environmental change, local food environments, human health and wellbeing.

Building upon the food system frameworks previously elaborated by Ericksen (2008) and Hammond and Dubé (2012), and drawing on the extensive, yet relatively disparate, literatures of health equity, environmental justice, human rights, and food sovereignty, respectively, we have developed an analytical framework for structuring the representation and analysis of food systems involving consumption of both subsistence foods, and food from the agri-food sector. The framework combines a food systems approach, with paradigms/methodologies from complexity science (in particular, systems dynamics theory) to represent major food system drivers and outcomes, including the multiple scales of food and nutrition security determinants. The framework further incorporates a structured analysis of the food system structure (including scale), and outcomes, in relation justice and equity, to identify the emergence of environmental injustices and health inequities from exogenously driven meta-scale forces. The framework was applied to elucidate critical processes and factors that drive outcomes of food and nutrition security in the Inuit food system in northern Canada. The Inuit food system was chosen as a case study due to the high prevalence of food insecurity and poor dietary quality (Huet, Rosol, & Egeland, 2012; Rosol et al., 2011), the rapid dietary transition in recent decades (Kuhnlein, Receveur, Soueida, & Egeland, 2004), and the broad spectrum of environmental (Ford & Beaumier, 2011), economic, and sociocultural changes in the Canadian North.

BriGHT project

Biological samples of marine organisms (from phytoplankton to marine mammals) have been collected along the coasts of Nunavik throughout summer and fall 2017 during the Leg2a on the CCGS *Amundsen* and in collaboration with DFO. Two master's students are currently proceeding with various analyses on marine samples that aim to evaluate the composition of phytoplankton, zooplankton and benthos samples collected in 2017. Organization of a fieldwork session to collect ice algae is currently underway for March-April 2018, with the goal of better covering the whole arctic marine food web.

The collection of field samples for the Arctic char aspect of the project is progressing as planned and more than half of the samples are now collected. A field campaign for the summer of 2018 is being organized and the processing of samples for the Arctic char genomic aspect of the project is also progressing. The Q2017 was also conducted on board the CCGS *Amundsen* after the Leg2a later in summer and fall. A total of 1327 Inuit from the 14 Nunavik communities and aged 16 years old and above participated, provided biological samples, conducted medical testing and answered questionnaires. Q2017 samples analysis (IP25 and other fatty acids profile, vitamin A, etc.) will be started progressively next March 2018. Two MSc students and one postdoctoral fellow will be recruited for the health-related aspects of the BriGHT project in the coming months.

DISCUSSION

Biomonitoring research reveals very different issues between Indigenous regions. Among First Nations communities involved in the JES!-YEH! project, Hg and Pb exposure were quite low and not very 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 BB 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 foods while avoiding Pb exposure. Considering the elevated prevalence of iron deficiency, anemia, elevated Mn and Co, obesity, diabetes and poor diet quality 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 the progression of multiple-burden of diseases among indigenous youth.

Conversely, in Nunavik, Hg exposure among pregnant women (NQN project) 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 projects analysing Hg exposure annual 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 and among other circumpolar regions.

Moreover, in Nunavik, few pregnant women participants (5%) continued to have 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 Nation communities, joins efforts between researchers and several Nunavik partners, including those outside the health sector, are important to jointly address contaminant exposure and anemia issues in Nunavik and elsewhere.

Both JES!-YEH! and NQN projects revealed that although most POPs exposure is nowadays quite low, the elevated levels of PFNA, a more recent PFC, highlight that longer-chain molecules now replaced older PFCs such as PFOS and PFOA. Further local investigation is needed to tentatively identify the local source of PFNA exposure among children in the JES!-YEH! project. It is of note that in 2016 the Government of Canada has amended the Canada's Prohibition of Certain Toxic Substances Regulations to add long-chain PFCs including PFNA (Environment and Climate Change Canada, 2017). However, since these substances are persistent and accumulate in the Arctic food chain, exposure levels in Nunavik may not decrease rapidly. High levels less persistent chemicals like bisphenol A and monobenzyle phtalate were also found in the First Nation youth, and further analysis will confirm whether the high consumption of ultra-processed market foods are the main contributor to such exposure. Globally, this shows that large screening for new chemicals, and not only for those transported over long distances but also the less persistent ones from local sources, is important for better understanding the impact of local development and global dietary changes in indigenous communities.

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).

In addition, our most recent data analysis in Q2004 participants show that RBC selenoneine concentrations in women were surprisingly almost double that of men, even after controlling for age, region, and dietary factors in the multiple linear regression model ($p<0.001$). Higher RBC selenoneine among women may reflect potential differential response bias during food frequency questionnaires, biological sex differences, or gender-specific dietary habits.

Elevated RBC and whole blood Se among Arctic Inuit populations, as well as non-linear associations between whole blood Se and plasma Se found in Nunavik and Greenland (Achouba et al., 2016; Hansen et al. 2004) are likely due to accumulation of selenoneine in RBCs resulting from consumption of marine country foods. In particular, such trends may result from high consumption of beluga mattaaq and/or of other toothed-whale mattaaq. Indeed, beluga mattaaq consumption was highly correlated with RBC selenoneine ($p<0.001$) after controlling for age, sex, region, and other dietary factors. Furthermore, differential intake of beluga mattaaq may be responsible for the associations between RBC selenoneine and market meat consumption (e.g. market meat consumers eat less beluga mattaaq), region (e.g. Hudson Strait communities have increased access to beluga since it's the primary region for beluga hunting in Nunavik), and age (e.g. older Inuit often consume more beluga mattaaq) (Kuhnlein et al. 1996; Lemire et al. 2015).

While some evidence suggests that selenoneine consumption may mediate the negative health effects of MeHg, future studies will examine the biological functions of selenoneine and provide an evidence base for locally-driven public health recommendations that weigh the potential benefits and risks of consuming country foods that are simultaneously high in selenoneine, low in MeHg, while considering other nutrients and contaminants.

CONCLUSION

Actual research findings highlight the complexity of food and contaminants related issues in the North, since communities are currently facing 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 pressures on local food resources. Conversely, several great leaders are mobilized for positives changes in their communities and Q2017 is a great example of this Indigenous re-appropriation of local health governance and healing practices (http://www.ledevoir.com/societe/actualites-en-societe/502283/amundsen-recherche). 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 a unique opportunity to consolidate several ongoing research projects in northern environmental and indigenous health at Université Laval, and the most recent project on global changes and Inuit and First Nation 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-edge science and community-based research. The next year will focus on Junior 2 FRQS fellow application, data analysis, manuscript publications, community and regional report dissemination and preparation of future FENHCY study. The following months will also be critical to recruit more graduate students and secure funding for the Nasivvik Research Chair after 2018.

This ArcticNet project has contributed to generate multiple outcomes and impacts that are summarized in Table 7.

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T.able 7. Outcomes and Impacts generated by different projects conducted during this ArcticNet project.

Biomonitoring of environmental contaminants in northern populations and local foods	
First Nation Youth, Environment and Health pilot project (JES!-YEH!)	• This pilot project highlighted the low exposure to Hg and Pb from traditional foods but the increasing presence of emerging contaminants (bisphenol A, more recent perfluorinated compounds, phtalates), the high prevalence of anemia, blood manganese, obesity, food insecurity, overcrowding and the poor diet quality among children and youth from four First Nation communities in Quebec. • These findings inform the future the pan-Canadian Food, Environment, Nutrition and Health of First Nations Children and Youth (FENHCY) Study envisioned for 2018-2019.
Nutaratsaliit qanuingisiarningit niqituinnanut Project (NQN) / Pregnancy wellness with country foods Project	• These data show the high exposure to Hg and increasing exposure to more recent perfluorinated compounds among Nunavik pregnant women. These results contribute to the biomonitoring efforts at the national and international levels (NCP, AMAP, UNEP). They are critical for the biomonitoring plans being established under the Stockholm and the Minamata Conventions and for the periodic evaluation of their effectiveness. • These data will be used to better assess temporal and regional variations in Hg exposure among pregnant women and identify local country foods responsible for these variations. • These findings are mandatory to support the update and review of clinical algorithms for the follow-up of patients with elevated exposure to Hg and Pb in Nunavik and for developing screening tools. These tools would help identify pregnant women with elevated Hg and Pb exposure, and undertake clinical actions early during pregnancy to better prevent Hg and Pb exposures and promote health and well-being from pregnancy to early childhood.
Qanuilirpitaa 2017 (Q2017) – metal and long-range contaminant exposures	• A total de 1327 participants were recruited between August and October 2017. • These data will support the assessment of metal and POPs exposure time-trends among Nunavik adults (Q2004-Q2017) and their associated health outcomes. • These data contribute to the biomonitoring efforts at the national and international levels (NCP, AMAP, UNEP). They are critical for the biomonitoring plans being established under the Stockholm and the Minamata Conventions and for the periodic evaluation of their effectiveness.
Selenoneine Nunavik country foods	• This project will help to identify key species rich in selenoneine as well as predict the consequences of climate change on selenium and fatty acid distribution in marine foods consumed by the Inuit.
Nunavik country foods and lead in migratory birds	• These findings will support the communication campaign to be launched by the NRBHSS to prevent exposure of Nunavimmiut to Pb in 2018.

Human health effects of contaminants and contaminant/nutrient interactions	
Environmental contaminants and plasma metabolite profiles	• These metabolomics data will help to identify biochemical pathways, metabolites and unique signatures associated with exposure to contaminants, nutrient intake and the development of cardiometabolic diseases in Nunavik.
New selenoneine data and reanalysis of the Nunavik Child Development Study (NCDS) and Qanuippitaa 2004 (Q2004) datasets	• This project shows that selenoneine is the primary form of selenium in Nunavik adult blood, and that the levels are significantly higher among those consuming beluga mattaaq, among women and those from the Hudson Strait villages. • This project is assessing the health-related effects of selenoneine in children and adults for the first time. • These findings will be critical for the finalisation of the Selenium risk assessment initiative on-going at Health Canada. • These findings will also be included in the next version of the clinical guidelines for the follow-up of Hg exposure among Nunavik pregnant women. • These results will improve our capacity to develop and implement interventions that aim to promote the benefits of country foods of marine origin, while minimizing Hg toxicity and cardiometabolic outcomes in Nunavik.
Zoonosis and other infectious agents	
Q2017 – zoonosis and infectious diseases	• This project will provide actual information on zoonotic and infectious important diseases in Nunavik (*Toxoplasma gondii*, *Helicobacter pylori* and *Cryptosporidium* ssp.) to understand how Inuit are exposed to them, their related-health effects, and to develop tools and strategies to promote healthy individuals and communities while practicing traditional activities, in partnership with local and regional stakeholders.
Effects of local and regional development	
Q2017 – less persistent contaminant exposure	• These findings will provide the first data on less persistent contaminant exposure from local activities (landfill, oil spills, etc.), market foods and other consumer goods in the Arctic.
Impact of climate and ecosystem changes on local food systems and on northern health	
GreenEdge	• These results will support Inuit 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 environmental changes. • A NCP proposal was submitted Jan 10, 2018, to consult the Qikiqtarjuaq community members through the modelisation process and to eventually undertake a follow-up dietary and biomonitoring study in 2019.
Bridging Global change, Inuit Health and the Transforming Arctic Ocean (BriGHT)	• These results will allow us to model plausible climate-driven trajectories in local marine foods characteristics and their likely impact on Inuit health and wellbeing, assisting with the formulation of locally-adapted mitigation adaptation strategies aimed at promoting Inuit local food systems and security in Nunavik.

Knowledge mobilization	
Info-MADO, clinical algorithms for Hg and Pb and screening questionnaire for Hg exposure	• All these knowledge translation documents will strengthen health professionals' capacity in Nunavik to act in prevention, and reduce Hg and Pb exposure early during pregnancy and to promote healthy pregnancies and children while eating country foods.
JES!-YEH! pilot project – findings on childhood anemia prevention and diet-related issues	• These findings led to the mobilization of several communities, regional and federal partners for eventually developing an action plan to prevent childhood and youth iron deficiency and anemia, obesity and diabetes and improve diet quality in First Nations communities in Quebec.
20 "Must-read" scientific articles in Inuit health	• This project did a literature review and selected the top 20 "must-read" recent scientific papers about Inuit health to increase knowledge translation to clinicians and public health practitioners regarding the most recent research on Inuit health. • Once a month, a newsletter summarizing a selection of these 20 papers will be sent by email to Nunavik health practitioners and will be posted on the Nasivvik Chair Facebook page.
Nasivvik Chair website, Joint Nasivvik Chair and Nasivvik Centre kiosk at Arctic Change 2018, Facebook page and Documentaries projections	• These activities contribute to create a community of practice in northern ecosystems and health at ULaval and elsewhere, and to increase awareness of the general public about these issues. • Website: http://en.nasivvik.chaire.ulaval.ca/ • Facebook: https://www.facebook.com/Nasivvik/ (195 followers)
Nasivvik *Éric Dewailly* annual scholarship	• This scholarship strengthens the capacity of graduate students to develop the skills required for participatory research and mobilizing their project findings into actions in the communities (http://en.nasivvik.chaire.ulaval.ca/eacuteric-dewailly-scholarship.html)
Best research practices in indigenous health	• These activities support the INQ and ULaval in developing the highest ethical standards for indigenous health and global health research.
Open letters	• These publications recognize : (i) the contribution, over the past 30 years, of more than 3000 Nunavimmiut that participated in contaminant research, (ii) that 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 and of the Minamata Convention in 2017, and (iii) that Nunavimmiut who participated in these studies directly helped to reduce POPs exposure in the Arctic and worldwide.
Reference book on Nunavik wildlife parasites and zoonotic diseases	• This collaborative hands-on reference book will help Inuit decrease their exposure to wildlife parasites and prevent zoonotic diseases in the region.
Human Health Assessment Groups of the AMAP (HHAG-AMAP) and United Nations Environment Program (UNEP) groups	• These expertise contributions inform future health research about contaminants and health in circumpolar countries. • Biomonitoring and health outcomes research (Obj 1 and 2) are part of the groundwork for assessing the efficacy of the Stockholm and Minamata Conventions.

REFERENCES

ACCLPP. 2012. CDC response to advisory committee on childhood lead poisoning prevention recommendations in " low level lead exposure harms children: A renewed call of primary prevention ". Atlanta.

Achouba A, Dumas P, Ouellet N, Lemire M, Ayotte P. 2016. Plasma levels of selenium-containing proteins in inuit adults from nunavik. Environ Int 96:8-15.

Adamou T, Muckle G, Riva M, Ayotte P. In preparation. Maternal exposure to lead (Pb) in nunavik: A temporal trend analysis.

Adamou T, Riva M, Muckle G, Anassour Laouan-Sidi E, Lemire M, Dery S, et al. In revision. Temporal trend (1992-2013) of blood mercury and plasma polychlorinated biphenyls concentrations among pregnant inuit women from nunavik. In revision.

AMAP. 2011. AMAP Assessment 2011: Mercury in the Arctic. Olso, Norway.

AMAP. 2014. AMAP Technical report no. 7: Trends in stockholm convention persistent organic pollutants (POPs) in arctic air, human media and biota. Olso, Norway.

AMAP. 2015. AMAP Assessment 2015: Human health in the arctic. Oslo, Norway.

AMAP. 2016. AMAP Assessment 2016: Chemicals of Emerging Arctic Concern. Olso, Norway.

Assembly of First Nations. 2013. First nation biomonitoring initiative (FNBI) national results (2011).

Braune B, Chetelat J, Amyot M, Brown T, Clayden M, Evans M, et al. 2015. Mercury in the marine environment of the canadian arctic: Review of recent findings. Sci Total Environ 509-510:67-90.

CHMS. 2010. Report on human biomonitoring of environmental chemicals in canada: Results of the canadian health measures survey cycle 1 (2007–2009). Ottawa: Health Canada.

CHMS. 2013. Second report on human biomonitoring of environmental chemicals in canada: Results of the canadian health measures survey cycle 2 (2009–2011).434 pp.

Choi AL, Budtz-Jorgensen E, Jorgensen PJ, Steuerwald U, Debes F, Weihe P, et al. 2008. Selenium as a potential protective factor against mercury developmental neurotoxicity. Environ Res 107:45-52.

Cole TJ, Lobstein T. 2012. Extended international (IOTF) body mass index cut-offs for thinness, overweight and obesity. Pediatr Obes 7:284-294.

Cooper, M., Greene-Finestone, L., Lowell, H., Levesque, J., Robinson, S. 2012. "Iron Sufficiency of Canadians." Health Reports / Statistics Canada, Canadian Centre for Health Information = Rapports Sur La Santé / Statistique Canada, Centre Canadien D'information Sur La Santé, 23 (4), 41–48.

Couture A, Levesque B, Dewailly E, Muckle G, Dery S, Proulx JF. 2012. Lead exposure in Nunavik: From research to action. Int J Circumpolar Health 71:18591.

Damman, S., Eide, W.B., Kuhnlein, H.V. 2008. Indigenous peoples' nutrition transition in a right to food perspective. Food Policy 33:135–155.

Donaldson SG, Van Oostdam J, Tikhonov C, Feeley M, Armstrong B, Ayotte P, et al. 2010. Environmental contaminants and human health in the canadian arctic. Science of the Total Environment 408:5165-5234.

Ducrocq J, Simard M, Proulx JF, Lévesque B, Lemire M. In preparation. Contribution of local knowledge in the investigation and management of a public health issue: An ecohealth approach applied to a trichinellosis outbreak in nunavik (Québec, Canada).

ECCC. 2016. Réglementation sur les oiseaux migrateurs au Canada, juillet 2016. Ottawa.

ECCC. 2017. Current Regulations Prohibition of Certain Toxic Substances Regulations, 201(SOR/2012-285): www.ec.gc.ca/lcpe-cepa/fra/reglements/DetailReg.cfm?intReg=207.

Ericksen, P.J. 2008. Conceptualizing food systems for global environmental change research. Global Environmental Change 18: 234–245.

Fachehoun RC, Levesque B, Dumas P, St-Louis A, Dube M, Ayotte P. 2015. Lead exposure through consumption of big game meat in quebec, canada: Risk assessment and perception. Food Addit Contam Part A Chem Anal Control Expo Risk Assess 32: 1501-1511.

Flanagan, P.R., Haist, J., Valberg, L.S. 1980. Comparative effects of iron deficiency induced by bleeding and a low-iron diet on the intestinal absorptive interactions of iron, cobalt, manganese, zinc, lead and cadmium. J Nutr., 110(9), 1754-63.

Ford, J.D., Beaumier, M.C. 2011. Feeding the family during times of stress: experience and determinants of food insecurity in an Inuit community. The Geographical Journal 177: 44–61.

Ganther HE, Goudie C, Sunde ML, Kopecky MJ, Wagner P. 1972. Selenium: Relation to decreased toxicity of methylmercury added to diets containing tuna. Science 175:1122-1124.

Government of Nunavut. 2013. Nutrition fact sheets series - inuit traditional foods.

Hammond, R.A., Dubé, L. 2012. A systems science perspective and transdisciplinary models for food and nutrition security. PNAS 109:12356–12363.

Hansen JC, Deutch B, Pedersen HS. 2004. Selenium status inGgreenland inuit. Science of the Total Environment 331:207-214.

Health Canada. 2015. Third report on human biomonitoring of environmental chemicals in canada: Results of the canadian health measures survey (chms) cycle 3 (2012–2013). Ottawa.

IOM (Institute of Medicine). 2006. Dietary Reference Intakes: The Essential Guide to Nutrient Requirements. The National Academies Press, Washington, DC, 1334p.

Herrmann, T.M., Sandström, P., Granqvist, K., D'Astous, N., Vannar, J., Asselin, H., Saganash, N., Mameamskum, J., Guanish, G., Loon, J.-B., Cuciurean, R. 2014. Effects of mining on reindeer/caribou populations and indigenous livelihoods: community-based monitoring by Sami reindeer herders in Sweden and First Nations in Canada. The Polar Journal 4: 28–51.

Hoover, E. 2013. Cultural and health implications of fish advisories in a Native American community. Ecological Processes 2: 4.

Huet, C., Rosol, R., Egeland, G.M. 2012. The prevalence of food insecurity is high and the diet quality poor in Inuit communities. J. Nutr. 142: 541–547.

Kuhnlein, H.V., Receveur, O., Soueida, R., Egeland, G.M. 2004. Arctic indigenous peoples experience the nutrition transition with changing dietary patterns and obesity. J. Nutr. 134:1447–1453.

ITK, ICC. 2012. Inuit and the right to food: Inuit submission to un rapporteur on right to food. Ottawa:Inuit Tapiriit Kanatami (ITK) and the Inuit Circumpolar Council (ICC).

Legagneux P, Suffice P, Messier JS, Lelievre F, Tremblay JA, Maisonneuve C, et al. 2014. High risk of lead contamination for scavengers in an area with high moose hunting success. PLoS One 9:e111546.

Legrand M, Feeley M, Tikhonov C, Schoen D, Li-Muller A. 2010. Methylmercury blood guidance values for canada. Can J Public Health 101:28-31.

Lemire M, Kwan M, Laouan-Sidi AE, Muckle G, Pirkle C, Ayotte P, et al. 2015. Local country food sources of methylmercury, selenium and omega-3 fatty acids in nunavik, northern quebec. Sci Total Environ 509-510:248-259.

Lemire M, Furgal C, Ayotte P, Pirkle C, Boyd A, Muckle G, Ricard S, Gauthier MJ, Beaulne C, Allard E, Kwan M, Adamou T, Turgeon A. 2017. Exposure to food chain contaminants in Nunavik: evaluating spatial and time trends among pregnant women & implementing effective health communication for healthy pregnancies and children (Year 1 of 3). NCP synopsis 2017.

Lennert AE. 2016. What happens when the ice melts? Belugas, contaminants, ecosystems and human communities in the complexity of global change. Mar Pollut Bull 107:7-14.

Liberda EN, Tsuji LJ, Martin ID, Ayotte P, Dewailly E, Nieboer E. 2014. The complexity of hair/blood mercury concentration ratios and its implications. Environmental research 134:286-294.

Loring, P., Gerlach, S.C. 2009. Food, culture, and human health in Alaska: an integrative health approach to food security. Environmental Science & Policy 12: 466–478.

Lye E, Legrand M, Clarke J, Probert A. 2013. Blood total mercury concentrations in the canadian population: Canadian health measures survey cycle 1, 2007-2009. Can J Public Health 104:e246-251.

Messier V, Levesque B, Proulx JF, Rochette L, Libman MD, Ward BJ, et al. 2009. Seroprevalence of *Toxoplasma gondii* among Nunavik Inuit (Canada). Zoonoses Public Health 56:188-197.

NCP. 2013. Canadian arctic contaminants assessment report iii (cacar): Persistent organic pollutants in canada's north. Ottawa, ON.

NCP. In Press. Canadian Arctic Contaminants Assessment Report V (CACAR). Ottawa, ON.

Pétrin-Desrosiers C. 2016. Lead reduction strategy: A report on the availability and use of ammunitions in the 14 northern villages of nunavik (Quebec). Kuujjuaq.

Pirkle CM, Muckle G, Lemire M. 2016. Managing mercury exposure in northern canadian communities. CMAJ 188:1015-1023.

Plante C, Blanchet C, Rochette L, O'Brien HT. 2011. Prevalence of anemia among inuit women in nunavik, canada. Int J Circumpolar Health 70:154-165.

Ricard S, Lemire M. 2017. Info-MADO newsletter of the nunavik department of public health on notifiable diseases: The health professional's role in the current research project in nunavik: Nutaratsaliit qanuingisiarningit niqituinnanut - pregnancy wellness with traditional foods. Kuujjuaq.

Roberts, K.C., Shields, M., de Groh, M., Aziz, A., Gilbert, J.-A. 2012. Overweight and obesity in children and adolescents: Results from the 2009 to 2011 Canadian Health Measures Survey. Health Rep., 23, 37-41.

Rosol, R., Huet, C., Wood, M., Lennie, C., Osborne, G., Egeland, G.M. 2011. Prevalence of affirmative responses to questions of food insecurity: International Polar Year Inuit Health Survey, 2007-2008. Int J Circumpolar Health 70: 488–497.

Rosol R, Powell-Hellyer S, Chan HM. 2016. Impacts of decline harvest of country food on nutrient intake among inuit in arctic canada: Impact of climate change and possible adaptation plan. Int J Circumpolar Health 75:31127.

Sharp D. 2009. Environmental toxins, a potential risk factor for diabetes among canadian aboriginals. Int J Circumpolar Health 68:316-326.

Schlosberg, D. 2007. Defining Environmental Justice: Theories, Movements, and Nature. OUP Oxford.

Simpson, L., 2003. Toxic contamination undermining Indigenous food systems and Indigenous sovereignty. Pimatiziwin: A Journal of Aboriginal and Indigenous Community Health 1:130-134.

Statistics Canada. 2011. Enquête nationale auprès des ménages de 2011. www.statcan.gc.ca/pub/89-645-x/2015001/housing-logement-fra.htm.

Statistics Canada. 2015. Household food insecurity, 2011-2012. www.statcan.gc.ca/pub/82-625-x/2013001/article/11889-eng.htm.

Tang-Peronard JL, Heitmann BL, Andersen HR, Steuerwald U, Grandjean P, Weihe P, et al. 2014. Association between prenatal polychlorinated biphenyl exposure and obesity development at ages 5 and 7 y: A prospective cohort study of 656 children from the faroe islands. Am J Clin Nutr 99:5-13.

WHO. 2011. Haemoglobin concentrations for the diagnosis of anaemia and assessment of severity (Vitamin and Mineral Nutrition Information System). Geneva:World Health Organization.

Whyte, K. 2017. Food Sovereignty, Justice and Indigenous Peoples: An Essay on Settler Colonialism and Collective Continuance, in: Barnhill, A., Doggett, T., Egan, A. (Eds.), Oxford Handbook on Food Ethics.

Yamashita M, Yamashita Y, Ando T, Wakamiya J, Akiba S. 2013. Identification and determination of selenoneine, 2-selenyl-n alpha , n alpha , n alpha -trimethyl-l-histidine, as the major organic selenium in blood cells in a fish-eating population on remote japanese islands. Biol Trace Elem Res 156:36-44.

Yamashita Y, Yamashita M. 2010. Identification of a novel selenium-containing compound, selenoneine, as the predominant chemical form of organic selenium in the blood of bluefin tuna. J Biol Chem 285:18134-18138.

Yamashita Y, Yamashita M, Iida H. 2013. Selenium content in seafood in japan. Nutrients 5:388-395.

Ye Q, Park JE, Gugnani K, Betharia S, Pino-Figueroa A, Kim J. 2017. Influence of iron metabolism on manganese transport and toxicity. Metallomics.

Zota AR, Phillips CA, Mitro SD. 2016. Recent fast food consumption and bisphenol a and phthalates exposures among the u.S. Population in nhanes, 2003-2010. Environ Health Perspect 124:1521-1528.

PUBLICATIONS

Rapinski M, Cuerrier A, Harris C, Elders of Ivujivik, Elders of Kangiqsujjuaq, Lemire M. (In press). Our Sea, our Health, Avataq Cultural Institute.

Fillion M, Ricard S, Lévesque B, Brisson M, Lemire M. (In press). Protocole d'investigation et de suivi en regard de l'exposition au plomb au Nunavik – Mise à jour. Nunavik Regional Board of Health and Social Services, 30p.

Lemire M, Atikessé L, Jodoin S, Tahir E, Bradette-Laplante M, Gagné É, Guedes JC, Anassour LS E, Communauté de Nutashkuan, Bruneau S, McHugh GL N, Lucas M, Riva M, Muckle G, Ayotte P (2018). JES!-YEH! Projet pilote Jeunes, Environnement et Santé des Premières Nations - First Nations Youth, Environment and Health Pilot Project. Rapport pour Nutashkuan - 2015, 111p.

Lemire M, Atikessé L, Jodoin S, Tahir E, Bradette-Laplante M, Gagné É, Guedes JC, Anassour LS E, Communauté d'Unamen Shipu, Bruneau S, McHugh GL N, Lucas M, Riva M, Muckle G, Ayotte P. (2018). JES!-YEH! Projet pilote Jeunes, Environnement et Santé des Premières Nations - First Nations Youth, Environment and Health Pilot Project. Rapport pour Unamen Shipu - 2015, 110p.

Lemire M, Atikessé L, Jodoin S, Tahir E, Bradette-Laplante M, Gagné É, Guedes JC, Anassour LS E, Communauté de Lac Simon, Bruneau S, McHugh GL

N, Lucas M, Riva M, Muckle G, Ayotte P. (2017). JES!-YEH! Projet pilote Jeunes, Environnement et Santé des Premières Nations - First Nations Youth, Environment and Health Pilot Project. Rapport pour Lac Simon - 2015, 113p.

Lemire M, Atikessé L, Jodoin S, Tahir E, Bradette-Laplante M, Gagné É, Guedes JC, Anassour LS E, Communauté de Winneway – Long Point, Bruneau S, McHugh GL N, Lucas M, Riva M, Muckle G, Ayotte P. (2017). JES!-YEH! Projet pilote Jeunes, Environnement et Santé des Premières Nations - First Nations Youth, Environment and Health Pilot Project. Rapport pour Winneway - 2015, 111p.

Lemire M, Atikessé L, Jodoin S, Tahir E, Bradette-Laplante M, Gagné É, Guedes JC, Anassour L. Sidi E, Communauté de Lac Simon, Community of Winneway – Long Point First Nation, Communauté de Nutashkuan - CSSS Tshukuminu Kanani de Nutashkuan, Communauté de Unamen Shipu, Bruneau S, Gros-Louis N, Lucas M, Riva M, Muckle G, Ayotte P (2017). JES!-YEH! Projet pilote Jeunes, Environnement et Santé des Premières Nations - First Nations Youth, Environment and Health Pilot Project. Rapport pour Santé Canada. Centre de recherche du CHU de Québec, 507p.

Ricard S and Lemire M. (2017). Info-MADO: Newsletter of the Nunavik Department of Public Health on Notifiable diseases: The health professional's role in the current research project in Nunavik: Nutaratsaliit qanuingisiarningit niqituinnanut, 12p.

Curren M, Adlard B, Krummel E, Laird B, Ayotte P, Chan L, Muckle G, Lemire M, Tomlinson S (2016, in press). Canadian Arctic Contaminants Assessment Report (CACAR) IV: Human health assessment. Northern Contaminant Program, Government of Canada.

Lemire M, Muckle G, Déry S, Ricard S, Pirkle C. (2016, in revision). The complex balance between mercury exposure and country foods benefits – Comprehensive guidelines for health practitioners in Nunavik. Nunavik Regional Board of Health and Social Services, 40p.

SECTION IV. NORTHERN POLICY AND DEVELOPMENT

Section IV is composed of one ArcticNet research project discussing national and international policies in relation to the Canadian Arctic socio-economic development in a context of the rapid environmental changes and modernization.

A ‘REGIONAL SEAS ARRANGEMENT’ FOR THE ARCTIC OCEAN

Project Team

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ABSTRACT

The Arctic Ocean is a complex marine system in which currents, ice, fish, and marine mammals constantly move across the national boundaries of five coastal states (Canada, Greenland-Denmark, Norway, Russia, and the United States). Effective management of this system requires cooperation among Arctic Ocean coastal states, indigenous peoples, some non-Arctic states and inter-governmental organizations, and non-state actors such as environmental groups and shipping companies. To enhance cooperation among states, the UN Environmental Program (UNEP) has promoted the creation of “regional seas arrangements” (RSAs). Today, more than 143 states participate in 18 RSAs, such as the 1992 OSPAR Convention (Convention for the Protection of the Marine Environment of the North-East Atlantic). This project will examine how an Arctic Ocean RSA could be designed to: (1) promote and complement the roles of the Arctic Ocean coastal states and the role of the Arctic Council; (2) centrally include Arctic indigenous peoples; and (3) incorporate 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; air, land, and space-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 examined these options and the role that Arctic governments, the Arctic Council, indigenous peoples, scientists, shipping companies and other non-state actors can play.
- This project has also 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 unsymmetrical dimethyl-hydrazine, while the second issue concerns the arrival of large cruise ships in Canadian Arctic waters.
- This project enabled our team to engage in knowledge mobilization before and during the 2016 and 2017 voyages of the *Crystal Serenity* through the Northwest Passage. The voyage of this large cruise ship, and the informed debate that surrounded it, led Transport Canada to partner with Arctic eco-cruise operators and communities to develop guidelines for future voyages. The project leader has been involved in some of these discussions.

RESEARCH OBJECTIVES

The objectives of this project matched the two main goals of the Integrated Regional Impact Study framework, namely

1. to make knowledge understandable and available to everyone, but particularly for resource managers, decision makers at all political levels, and other stakeholders;
2. to analyze the impact of maritime pollution at a regional scale;
3. to provide policy and research recommendations to stakeholders; and
4. to examine cooperation in the region.

KNOWLEDGE MOBILIZATION

The project leader has published a number of op-ed articles based upon research supported by ArcticNet, including:

- "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

- "Northern voyage opens a new channel in diplomacy with China," Globe and Mail, 15 November 2017

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, and Al Jazeera. 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.

On 9 January 2018, the project leader attended a government-led consultation in Ottawa on the upcoming Arctic Policy Framework.

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 explored the options for increased international maritime cooperation in the Arctic, including through RSAs and bilateral arrangements. 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 unsymmetrical dimethyl-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, while the project leader has devoted some time to the research and publication of an article examining the reasons for continued Arctic cooperation after the 2014 Russian annexation of Crimea.

ACTIVITIES

The project, which was adjusted in response to new developments, accomplished the following:

Briefing session in Ottawa – In July 2016, a briefing session was held in Ottawa on the issue of Russia using the North Water Polynya as a disposal site for rocket stages fueled with highly toxic unsymmetrical dimethyl-hydrazine. 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 were held, including with 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 and Transport Minister), Alexander Darchiev (Ambassador of the Russian Foreign Ministry), Rolf Einar Fife (Norwegian Ambassador to France and former Legal Adviser to the Norwegian Foreign Minister), etc.

International Workshop – Due to changes in the Russia-NATO relationship, the Network Investigators modified the plans for a conference and held an international workshop instead. This was conducted in May 2017 with non-government experts and government officials from Russia, Norway, Denmark, United Kingdom, Netherlands, United States, Australia, Singapore, and Canada in attendance. The closed-door nature of the workshop enabled a full and frank sharing of information and analysis that would not have been possible in a conference format. The workshop contributed significantly to the development and sharing of knowledge about Arctic Ocean governance among experts and officials from all five Arctic Ocean states and beyond. It may also have smoothened the path for diplomacy and dispute resolution on Arctic maritime issues, including the December 2017 Agreement on Central Arctic Ocean Fisheries.

Publishing – The Network Investigators and Collaborators published extensively as a result of this project. For example, David VanderZwaag published 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); an article in Polar Record on "Toxic Splash: Russian rocket-stages dropped in Arctic waters raise health, environmental, and legal concerns"; and an article in International Relations on "Crises and International Cooperation: An Arctic Case Study. Suzanne Lalonde published 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). She also has a forthcoming article on "Canada's Influence on the Law of the Sea" published by the Centre for International Governance Innovation (CIGI) in Waterloo.

Conference attendance – The Network Investigators and Collaborators have spoken at numerous conferences on topics within this project. For example, Michael Byers and Suzanne Lalonde both spoke on the opening plenary panel at the ArcticNet Arctic Change 2017 Annual Conference and at an Arctic diplomacy workshop organized by the Canadian and Russian governments in November 2016. Lalonde also spoke on "Assessing Canada's Sovereignty over the Northwest Passage in a Changing Arctic" at a conference at Elmendorf Airforce Base in Alaska in April 2017; on "Innovating Arctic Governance" at the High North Dialogue in Bodo, Norway, in April 2017; on "The Polar Code: Its Impact on the Regulation of Shipping in the Arctic" at the Fletcher School at Tufts University in Boston in February 2017, and on "A Framework for a Pan-Arctic Network of Marine Protected Areas: Assessing the Challenges Ahead" at the Polar Cooperation Research Centre, Kobe University, Japan, in July 2016. David VanderZwaag spoke on "Polar

Regions and Marine Environmental Protection: Multilateral Progressions and Challenges" at a UN Environmental Program session in Joensuu, Finland; on "Governance of the Arctic Ocean beyond National Jurisdiction: Cooperative Currents, Restless Sea" at the IUCN World Conservation Congress in Honolulu, and on the "International Regulation of Arctic Ocean Fisheries, Shipping and Tourism: Cooperative Currents, Sea of Challenges" at the North Pacific Arctic Conference at the University of Hawaii.

RESULTS

We developed a comprehensive view of the existing literature as well as the diplomatic and legal landscape; adjusted our overall plan to engage in research, analysis and knowledge mobilization as a result of the changed relationship between Russia and NATO and other significant developments; conducted sustained research and consulted extensively; published numerous articles in peer-reviewed journals; and engaged in a great deal of knowledge mobilization, including op-ed articles in leading newspapers.

In the past two years, two new and potentially very important issues arose within the scope of our research: the arrival of a large cruise ship 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 unsymmetrical dimethyl-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 plans to 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.

In May 2017, the Network Investigators held an international workshop involving non-government experts and government officials from Russia, Norway, Denmark, United Kingdom, Netherlands, United States, Australia, Singapore, and Canada in attendance. The closed-door nature of the workshop enabled a full and frank sharing of information and analysis that would not have been possible in a conference format. The workshop contributed significantly to the development and sharing of knowledge about Arctic Ocean governance among experts and officials from all five Arctic Ocean states and beyond. It may also have smoothened the path for diplomacy and dispute resolution on Arctic maritime issues, including the December 2017 Agreement on Central Arctic Ocean Fisheries.

DISCUSSION

Russia annexed Crimea in March 2014. Although diplomacy on Arctic matters continued, 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 build a knowledge base that was broad enough to deal with new developments related to Arctic maritime governance. And indeed, two new issues soon arose: the arrival of a large cruise ship 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 unsymmetrical dimethyl-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.

Due to changes in the Russia-NATO relationship, the Network Investigators modified the plans for a conference and held an international workshop instead. This was conducted in May 2017 with non-government experts and government officials from Russia, Norway, Denmark, United Kingdom, Netherlands, United States, Australia, Singapore, and Canada in attendance. The closed-door nature of the workshop enabled a full and frank sharing of information and analysis that would not have been possible in a conference format. The workshop contributed significantly to the development and sharing of knowledge about Arctic Ocean governance among experts and officials from all five Arctic Ocean states and beyond. It may also have smoothened the path for diplomacy and dispute resolution on Arctic maritime issues, including the December 2017 Agreement on Central Arctic Ocean Fisheries. One clear result of the workshop was a long article published by the project leader in the journal International Relations, that explores and explains the reasons for continued Arctic cooperation after the 2014 annexation of Crimea.

CONCLUSION

The project has made excellent progress despite several necessary adjustments resulting from: (1) The effects of the 2014 Russian annexation of Crimea on international relations in the Arctic; (2) A resulting change in the United States' approach to the issue of Arctic Ocean governance during its 2015-2017 chairmanship of the Arctic Council; (3) The arrival of a large cruise ship in the Canadian Arctic; and (4) 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 unsymmetrical dimethyl-hydrazine.

The project successfully contributed to knowledge on Arctic Oceans governance despite—and in some cases because of—these developments, including with a long article in the journal International Relations examining and theorizing the reasons for continued cooperation during international crises, with the Arctic as a case study.

ACKNOWLEDGEMENTS

We wish to thank the Inuit Circumpolar Council—especially Okalik Eegeesiak and Stephanie Meakin—for the invaluable support they have provided to our research, analysis and knowledge mobilization. We also wish to thank officials in Global Affairs Canada, both political appointees and career civil servants, for their willingness to listen and respond to questions, research, analysis and advice. Special thanks are also due to David Balton, Timo Koivurova, Olav Stokke, and Anton Valsiliev.

REFERENCES

Betsy Baker, "The Developing Regional Regime for the Marine Arctic," in Erik Molenaar et al. (editors), The Law of the Sea and Polar Regions: Interactions Between Global and Regional Regimes (Dordrecht Martinus Nijhoff, 2013) pp. 35-59.

Betsy Baker and Brooks Yeager, "Coordinated Ocean Stewardship in the Arctic: Needs, Challenges and Possible Models for an Arctic Ocean Coordinating Agreement," (2015) 4(2) Transnational Environmental Law 359-394.

Michael Byers, International Law and the Arctic (Cambridge: Cambridge University Press, 2013).

Michael Byers, "The Law and Politics of the Lomonosov Ridge," in John Norton Moore & Tomas Heidar (eds.), Challenges of the Changing Arctic: Continental Shelf, Navigation, and Fisheries (Leiden: Brill, 2016) 42-52.

Michael Byers, "Crises and International Cooperation: An Arctic Case Study," (2017) 31(4) International Relations 375-402.

Michael Byers and Cameron Byers, Toxic Splash: Russian rocket-stages dropped in Arctic waters raise health, environmental, and legal concerns," (2017) 53(6) Polar Record 1-12.

Michael Byers and Andreas Østhagen, "Why does Canada have so many unresolved maritime boundary disputes?" (2016) 54 Canadian Yearbook of International Law 1-62.

J. Enno Harders, “In Quest of an Arctic Legal Regime: Marine Regionalism – A Concept of International Law Evaluated,” (1987) 11 Marine Policy 285.

Suzanne Lalonde, “Marine Protected Areas in the Arctic,” in A.O. Elferink et al. (editors), The Law of the Sea and Polar Regions: Interactions between Global and Regional Regimes (Brill: Leiden, 2013) pp. 85-111.

Suzanne Lalonde, “The Northwest Passage and Northern Sea Route: Sovereignty and Responsibilities” in E.C. Pérez and S. Iglesias Sanchez, eds., Global Challenges in the Arctic Region – Sovereignty, Environment and Geopoltical Balance (London: Routledge, 2017) 42-74.

Suzanne Lalonde, “Managing Maritime Disputes: The Canadian-American Experience” in C. Schofield, ed., Maritime and Territorial Disputes in the East-China Sea: Current Status and Ways to Reduce Tension. (Busan, Republic of Korea: Korea Maritime Institute, 2017) 77-98.

Suzanne Lalonde and Whitney Lackenbauer, “Chapter 7: The Territorial North and Canada’s International Arctic Security” in Heather Nicol & P. Whitney Lackenbaeur, eds., The Networked North: Borders and Borderlands in the Canadian Arctic Region (Waterloo: Centre on Foreign Policy and Federalism at St. Jerome’s University, 2017) 95-113.

Suzanne Lalonde and Whitney Lackenbauer, “Searching for Common Ground in Evolving Canadian and EU Arctic Strategies” in N. Liu, E.A. Kirk and T. Henriksen, eds., The European Union and the Arctic (Leiden: Brill / Nijhoff, 2017).

Erik Molenaar et al. (editors), The Law of the Sea and Polar Regions: Interactions Between Global and Regional Regimes (Leiden: Martinus Nijhoff, 2013).

Erik Molenaar, “Current and Prospective Roles of the Arctic Council System within the Context of the Law of the Sea,” (2012) 27 International Journal of Marine and Coastal Law 553.

David VanderZwaag, “Arctic” (2015) 25 Yearbook of International Environmental Law 254.

David VanderZwaag , “Climate Change and the Shifting International Law and Policy Seascape for Arctic Shipping. In R.S. Abate (ed), Climate Change Impacts on Ocean and Coastal Law. (Oxford University Press, 2015) 299-314.

David VanderZwaag, “The 2013 Minamata Convention and Protection of the Arctic Environment: Mercurial Promises and Challenges. (2015) 2 China Oceans Law Review 208-243.

David VanderZwaag, “Arctic Ocean Governance: Shifting Seascapes, Hazy Horizons” (2016) 24 Journal of International Cooperation Studies 15.

David VanderZwaag, “Governance of the Arctic Ocean beyond National Jurisdiction: Cooperative Currents, Restless Sea”in H.N. Scheiber, N. Oral and M. Kwon (editors), Ocean Law Debates: The 50 year Legacy and Emerging Issues for the Years Ahead (Leiden: Brill/ Martinus Nijhoff, 2017).

David VanderZwaag and Dawn Russell (eds), Recasting Transboundary Fisheries Management Arrangements in Light of Sustainability Principles: Canadian and International Perspectives (Leiden: Martinus Nijhoff, 2010).

David VanderZwaag and JR Edge, “Canada-Russia Relations in the Arctic: Conflictual Rhetoric, Cooperative Realities. In S. Lalonde and T.L. McDorman (eds), International Law and Politics of the Arctic Ocean: Essays in Honour of Donat Pharand. (Brill Nijhoff, Leiden, 2015) 240-265.

David VanderZwaag and Emily Mason. “Controlling the Long-range Transport of Persistent Organic Pollutants (POPs) into the Arctic: Progressions and Political Pairings” 352-374 In L.C. Jensen & G. Hønneland (eds), Handbook of the Politics of the Arctic, Cheltenham, (UK: Edward Elgar, 2015).

David VanderZwaag and Karen Scott , “Polar Oceans and Law of the Sea” In D.R. Rothwell et al (eds), The Oxford Handbook of the Law of the Sea. (Oxford University Press, Oxford, 2015) 724-751.

Alexander N. Vylegzhanin, Oran R. Young and Paul Arthur Berkman, "Governing the Barents Sea Region: Current Status, Emerging Issues, and Future Options" (2018) 49(1) Ocean Development and International Law 52.

Robin Warner et al., "Regional governance for fisheries and biodiversity," in S. M. Garcia et al. (editors), Governance of Marine Fisheries and Biodiversity Conservation: Interaction and Coevolution (John Wiley and Sons: Chichester, UK, 2014) pp. 211-224.

Brooks Yeager and Rob Huebert, A New Sea: The Need for a Regional Agreement on Management and Conservation of the Arctic Marine Environment (World Wildlife Fund, 2008).

SECTION V. KNOWLEDGE TRANSFER

Section V is composed of one ArcticNet research project focussing on knowledge mobilization in support of sustainable development in the Canadian Arctic.

POLAR DATA MANAGEMENT FOR NORTHERN SCIENCE

Project Team

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ABSTRACT

The Polar Data Catalogue (PDC, https://www.polardata.ca) at the University of Waterloo is one of Canada's primary sources for data and information on research in the polar regions. Formed as a partnership between the ArcticNet Network of Centres of Excellence, the Canadian Cryospheric Information Network (CCIN), the Department of Fisheries and Oceans Canada, and Noetix Research Inc., the PDC was created as a long-term repository and online access portal to serve the data management needs of ArcticNet and other Canadian and international polar research and monitoring programs. Since its online launch in 2007, the PDC has grown to include nearly 2,200 descriptive records of datasets and polar data resources and over 230,000 data files and satellite images. The PDC facilitates exchange of information among researchers, northern communities, the public, and other user groups. Through this project, the PDC and CCIN will enhance data management support to ArcticNet scientists and students. The project seeks to secure ArcticNet's long-term data legacy by streamlining and improving data submission and access, expanding visibility of ArcticNet's data through linkages with northern organizations and the global polar data management community and making ArcticNet's valuable data resources available far 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 (https://www.polardata.ca) (PDC) was developed in the mid-2000s as a data management system for ArcticNet scientists. Co-developed by ArcticNet, the Canadian Cryospheric Information Network (CCIN) 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 credibility and professional standards of the CCIN and PDC have been validated through the organization's accreditation as Canada's third member of the World Data System and as selection as Canada's National Antarctic Data Centre.
- Visibility of the PDC within the research and data management communities is gained though active participation in provincial, national, and international conferences. CCIN staff contribute to international and Canadian data management activities through participation in a variety of Arctic and Antarctic data management committees and organizations.
- CCIN contributes to the success and coordination of the Canadian polar data community through organizing and hosting two successful Canadian Polar Data Workshops in 2015 and 2017. With 120 participants between the two, the expectation is that this activity will continue every two years, with a 2019 Workshop hopefully occurring in northern Canada to facilitate northern community participation, especially as it pertains to future governance.
- The PDC team works continuously to develop and improve the online tools offered on the CCIN and PDC websites and to provide a secure preservation infrastructure for ArcticNet and other partners. Online traffic to our websites has increased over the years, with views and downloads of metadata, datafiles, and satellite imagery growing as our collections and outreach activities continue to mature.
- In 2017, a new PostGres open-source database was built and deployed at CCIN for PDC. This replacement of the old Oracle database provides flexibility for replication of the PDC away from the University of Waterloo campus such as building a PDC North in Cambridge Bay or other locations. In addition, the CCIN website (https://ccin.ca) (the Canadian node of the Global Cryosphere Watch) has been completely redesigned and released in January 2018, using a new, more modern interface.
- The PDC Help Manual has been updated, for additional user support, and new functions have been added to the PDC Input application, to give the PDC Data Manager better capability to manage metadata and data submissions, change owners of metadata and data, add and remove PDC Approvers, and upload complex datasets. Additionally, the PDC Search application user interface has been redesigned and rebuilt with added filters and usability and is expected to be released in 2018.
- Also in 2017, CCIN was commissioned by Environment and Climate Change Canada (ECCC) to create and distribute a survey concerning user needs of ice and snow data.

From over 100 responses, recommendations were made to ECCC for improving access and usability of these data for Canadians on the ECCC and CCIN websites.

- Progress was made this year in inventorying datasets and working with ArcticNet and other partner programs to complete their metadata contributions to the PDC. Forty-six new ArcticNet metadata records and 12 new datasets were entered into the PDC, for a total of 1065 approved ArcticNet metadata and 132 datasets, comprising 2,478,413 datafiles.
- Digital Object Identifiers (DOIs) have been assigned to 363 PDC datasets, including 65 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.
- Support for purchase of new hardware infrastructure or use of cloud storage solutions will need to be acquired in 2018 or 2019 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.

RESEARCH OBJECTIVES

This project, Polar Data Management for Northern Science, continues to expand the data stewardship infrastructure first envisioned by ArcticNet and CCIN almost 15 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:

- Support ArcticNet researchers to create, prepare, submit, and update their project metadata records and datafiles in the PDC, so that the legacy of ArcticNet research is available on the Internet for researchers, northern com- munities and organizations, international programs, and future generations;
- 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;
- Improve the online PDC Geospatial Search, PDC Metadata/Data Input, and PDC Lite Search tools to better serve ArcticNet researchers, northerners, and other users;
- Maintain and improve PDC hardware, software, and security infrastructure, including exploring options for cloud-based preservation and accessibility of the PDC data collections;
- Contribute to 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;
- Use the CCIN website to enhance outreach and education about Canada's north to students and the public; and
- 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 CCIN 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:

- 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;
- 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;
- Train and educate researchers and students in data management principles and practical use of the PDC;
- Formalize an outreach and communication program, including to students, to heighten awareness of data management principles and ensure visibility and maximal use of PDC and CCIN resources;
- Quantify CCIN and PDC services and associated costs for data management;
- Archive, serve, and link to satellite datasets that are of interest to the Canadian cryospheric and remote sensing research communities; and
- 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 CCIN/PDC, polar data management, and the polar regions to researchers, students, and other interested stakeholders.

Presentations at conferences providing published abstracts:

- Kanao, M., J. Friddell, and A. Kadokura, Metadata Management, Interoperability and Data Citation in Polar Science. Fifth International Symposium on Arctic Research, Tokyo, 2018. https://pdfwww.gakkai-web.net/gakkai/knt/isar_5/ISAR5_digest.pdf
- J. Friddell, P. Pulsifer, G. Alix, D. Church, Y. Dong, D. Fairbarn, D. Friddell, F. Lauritzen, and E. LeDrew, Linking People with People and with the Data They Need: Recent Activities at the Canadian Cryospheric Information Network and Polar Data Catalogue. Fifth International Symposium on Arctic Research, Tokyo, 2018. https://pdfwww.gakkai-web.net/gakkai/knt/isar_5/ISAR5_digest.pdf
- Christoffersen Vossepoel, S., M. Murray, D. Arthurs, C. Barnard, S. Carpendale, B. Chu, C. Duguay, A. Forest, J. Friddell, C. Herbert, S. Liang, G. Ljubicic, M. Maloley, S. Nickels, T. Papakyriakou, J. Parrott, P. Pulsifer, T. Scassa, D. Scott, J. Sokol, F. Taylor, W. Vincent and C. Wilson, The Canadian Consortium for Arctic Data Interoperability: An Initiative for Facilitating Canadian Arctic Data Sharing and Analysis. International Arctic Change Conference, Québec City, 2017. http://www.arcticnetmeetings.ca/ac2017/docs/AC2017-Abstracts.pdf
- Christoffersen Vossepoel, S., M. Murray, D. Arthurs, C. Barnard, S. Carpendale, B. Chu, C. Duguay, A. Forest, J. Friddell, C. Herbert, S. Liang, G. Ljubicic, M. Maloley, S. Nickels, T. Papakyriakou, J. Parrott, P. Pulsifer, T. Scassa, D. Scott, J. Sokol, F. Taylor, W. Vincent and C. Wilson, The Canadian Consortium for Arctic Data Interoperability. International Arctic Change Conference, Québec City, 2017. http://www.arcticnetmeetings.ca/ac2017/docs/AC2017-Abstracts.pdf
- Friddell, J., G. Alix, D. Church, Y. Dong, D. Friddell, N. Koylass, T. Koylass, F. Lauritzen,

E. LeDrew, and K. Sudarshanakumar, Increasing Access to Polar Data Through Visualization, Collaboration, and Policy. International Arctic Change Conference, Québec City, 2017. http://www.arcticnetmeetings.ca/ac2017/docs/AC2017-Abstracts.pdf

- Pulsifer, P., A. Van de Putte, P. Bricher, C. Strawhacker, M. Murray, D. Arthurs, T. Barnes, O. Bermúdez Molina, T. de Bruin, K. Buckland, J. Collins, R. Duerr, J. Friddell , Ø. Godøy, T. Hamre, H. Jóhannsson, U. Jonsell, S.J.S. Khalsa, E. Kruemmel, J. Larsen, C. Leone, S. Longo, M. Maloley, R. Nitu, A. Olivieri, M. Parsons, J. Parrott, H. Savela, S. Schumacher, S. Scory, D. Scott, M. Tacoma, S. Tronstad, A. Vitikka, S. Vossepoel, and H.H. Yi, Enhancing Polar Research and Decision Making: Advances in International Data Sharing Through Active Collaboration. International Arctic Change Conference, Québec City, 2017. http://www.arcticnetmeetings.ca/ac2017/docs/AC2017-Abstracts.pdf
- Friddell, J., G. Alix,, Y. Dong, D. Friddell, F. Lauritzen, and E. LeDrew, The Polar Data Catalogue: Best Practices for Sharing and Archiving Canada's Polar Data. International Workshop on Sharing, Citation and Publication of Scientific Data Across Disciplines, Tokyo, 2017. http://polaris.nipr.ac.jp/~pseis/data.ws-2017/ROIS-DS.Data-Workshop.2017_Abstract-Book.20171120.pdf
- LeDrew E., J. Friddell, D. Church, and G. Alix, The Northern Voice: Listening to Indigenous and Northern Perspectives on Management of Data in Canada. 37th International Symposium on Remote Sensing of Environment (ISRSE-37), Tshwane, South Africa, 2017.
- Pulsifer, P., D. Arthurs, J. R. Larsen, C. Strawhacker, J. Friddell, M. Tacoma, M. Parsons, A. Fleming, S. Tronstad, S. Scory, Ø. Godøy, D. Church, G. Alix, and L. Yarmey, Collaborative Development of Globally Connected Data and Information Systems for Arctic Observing: Results of the Polar Connections Interoperability Workshop. Arctic Science Summit Week, Prague, p. 204, 2017. http://www.assw2017.eu/files/assw2017-abstract-book.pdf
- Church, D., G. Alix, F. Lauritzen, D. Friddell, Y. Dong, E. LeDrew, and J. Friddell, Get Credit for Your Data: DOIs and the Polar Data Catalogue. Arctic Science Summit Week, Prague, p. 130, 2017. http://www.assw2017.eu/files/assw2017-abstract-book.pdf
- Church, D., G. Alix, J. Friddell, P. Pulsifer, and E. LeDrew, Data Repositories and DOIs: Your New BFFs? Association of Polar Early Career Scientists (APECS) 3rd International Online Conference "Outside the Box," 2017. https://www.apecs.is/events/past-event-highlights/event-highlights-2017/apecs-online-conference-2017.html

Other presentations at conferences and meetings:

- Data Management at UW, oral presentation, University of Waterloo Associate Directors of Research monthly meeting (2017).
- Data Management Essentials, oral presentation, International Arctic Change Conference Student Day, Québec City (2017).
- Data Management for NCP, online presentation, Northern Contaminants Program Management Committee community webinar (2017).
- RADARSAT Imagery of the Changing North: Satellite Data for Your Climate Research, oral presentation, GIS Day, University of Waterloo, Waterloo, ON (2017).
- Arctic Data Committee Annual Report 2017, oral presentation, ADC Meeting, Montréal (2017).
- Standing Committee on Antarctic Data Management Annual Report 2017, oral presentation, SC-ADM Meeting, Montréal (2017).

- Canadian Cryospheric Information Network: A GCW Portal for Canada, oral presentation, Arctic Polar Regional Climate Centre meeting, Montréal (2017).
- Polar Data Management, oral presentation and panel discussion for Valorization des données, Réunion annuelle Sentinelle Nord, Québec (2017).
- Invited panelist for breakout session on How do we support collaboration and strong DRI user communities? Leadership Council for Digital Research Infrastructure Summit, Toronto (2017).
- NGMP Data Management, online presentation, Nunavut General Monitoring Plan funded researchers' webinar (2017).
- Data management for biodiversity, oral presentation, Canada's Arctic Biodiversity: The Next 150 Years, Canadian Museum of Nature, Ottawa (2017).

Other knowledge mobilization activities:

- Co-convened session Understanding the Changing Arctic through Data: Stewardship, Publication, and Science. 5th International Symposium on Arctic Research, Tokyo, Japan, January 2018.
- Co-chaired session Advancing Data Sharing, Access, and Analysis for Understanding the Arctic. International Arctic Change Conference, Québec City, December 2017.
- Planned and hosted Second Canadian Polar Data Workshop, Ottawa, ON, May 2017 (https://secondcanadianpolardataworkshop.wordpress.com).
- Increased use of the PDC Twitter and Facebook accounts, including the launch of a forum on LinkedIn entitled Polar Data in Canada (https://secondcanadianpolardataworkshop.wordpress.com) which is intended for enhancing community linkage and communication, as requested at the Canadian Polar Data Workshop (further information in the Activities section below).
- Entry of the PDC into online databases and lists of data access portals, including the Portage Network's new Federated Research Data Repository.

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), 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-1990s. 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.

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. 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, during annual ArcticNet meetings, and most recently at the Canadian National Data Stewardship Framework Summit, hosted by Research Data Canada in late 2017. 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.

ACTIVITY

Specific tasks undertaken this year are outlined below, with further details provided 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 datafiles for their projects, including data from the Amundsen for 2004-2017.
- Worked with ArcticNet management to write and circulate to NI's a new Call for Data letter outlining requirement of metadata deposit into the PDC, as well as a request for data deposit in the PDC or an alternate recognized repository by 1 June 2018. If data are not deposited in the PDC, researchers were requested to send a link to the data in the alternate repository for inclusion in the PDC metadata.
- Improved the PDC Input application by adding front-end functionality to allow more streamlined management by the PDC Data Manager of submitted data and metadata.
- Updated the PDC Help Manual for increased support for researchers and other PDC users and created a new prototype of the PDC Search application with new filters and usability.
- Created and released a new PostgreSQL database, an open-source alternative to Oracle, which facilitates offsite replication of the PDC database to northern locations, such as PDC North in Cambridge Bay.

- 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.
- Held two Polar Data Management Committee meetings, in March and December 2017, to share progress, discuss issues, and receive feedback. The December meeting, at the Arctic Change conference, was the largest PDMC meeting in many years, with 20 people attending.
- Enhanced and maintained the CCIN/PDC computer infrastructure by updating server hardware, security, and backup functions.

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 new development funding.

Completed a community document, in collaboration with POLAR, NCP, and NGMP, entitled Data Management Principles and Guidelines for Polar Research and Monitoring in Canada (Canadian Cryospheric Information Network, Polar Knowledge Canada, Northern Contaminants Program, and Nunavut General Monitoring Plan. 2017. Data Management Principles and Guidelines for Polar Research and Monitoring in Canada. Retrieved from https://www.canada.ca/en/polar-knowledge/publications/data-management-principles-and-guidelines-2017-may.html), and developed a Data Deposit Agreement to be used by the three programs as formal acknowledgement by PIs of their data management responsibilities.

- Worked with staff from the Global Change Master Directory (GCMD) to convert and upload PDC's Antarctic metadata to GCMD, as required by our new role as Canada's National Antarctic Data Centre.
- Built and released a new CCIN website (Figure 1) using new web technologies, removing a potential security issue with the aging content management system that was replaced and automating numerous tasks for the data visualizations which had previously been done manually.
- Audited old metadata which required updating or had outstanding issues.
- Completed a report to ECCC based on survey results concerning user needs for snow and ice data, with the intention of using these results to improve functionality.

ArcticNet Metadata and Data Management, and Stewardship

This year, as of 29 January 2018, 46 new ArcticNet metadata records and 12 new datasets have been added to the PDC, for a total of 985 total approved metadata and 126 total datasets, comprising 2,478,413 datafiles. Further details are in the ArcticNet Project Metadata and Data List and in the Results and Metadata sections of this report. The ArcticNet Administrative and Data Coordinator at U. Laval, C. Gombault, continues allocating considerable time to organizing and uploading to the PDC the diverse ship datasets collected on the CCGS *Amundsen* since 2003, particularly Bioness CTD (Conductivity-Temperature-Depth) casts, TermoSalinoGraph (TSG) 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, has had assistance this year in reviewing and approving ArcticNet metadata and data submissions, due to her maternity leave. She and the temporary data management staff have made numerous contacts with researchers, especially with respect to data preparation, submission, and review. They have reviewed ArcticNet metadata and datafiles and have approved them for public release, as appropriate.

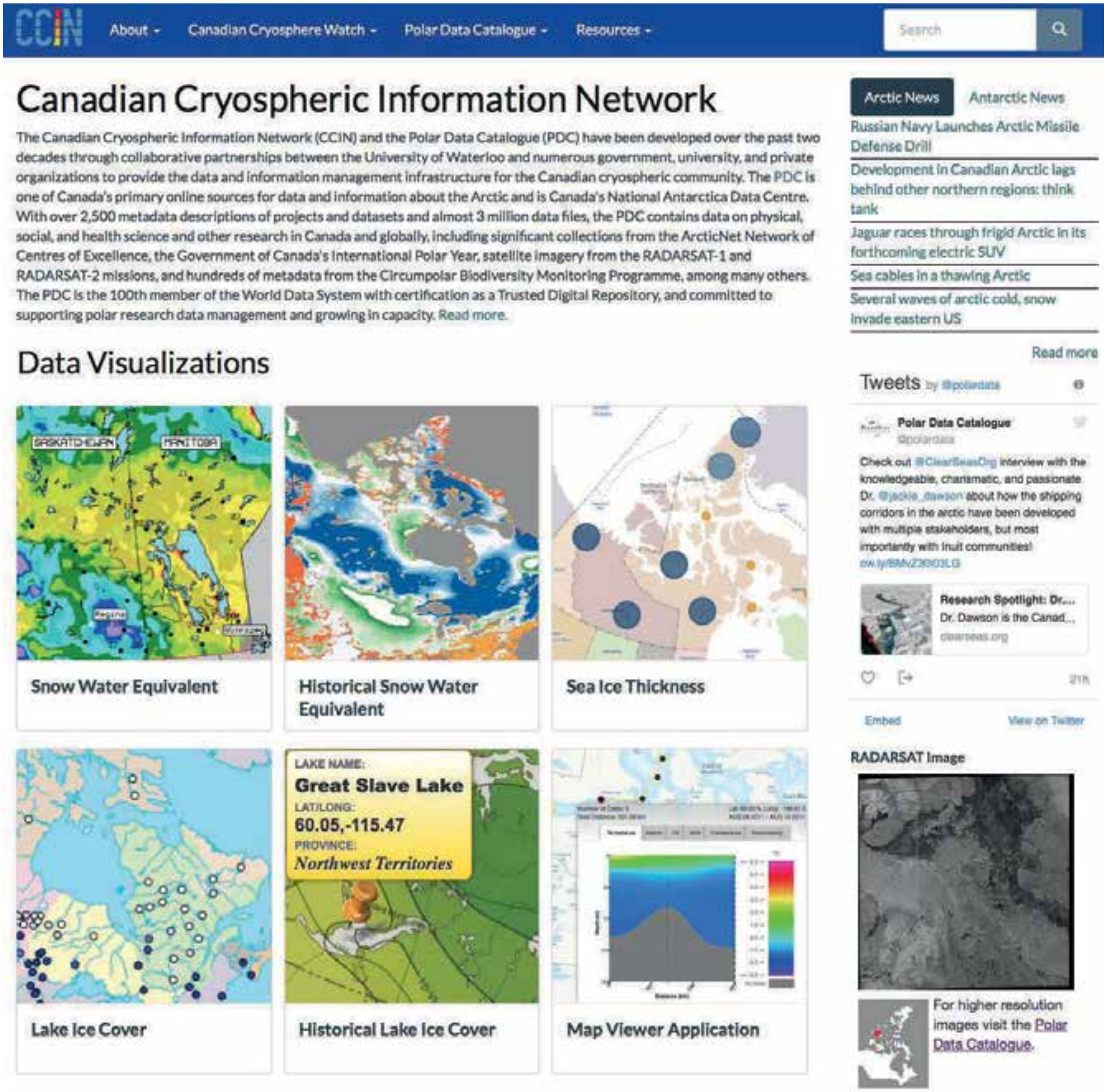

Figure 1. New CCIN Website.

Hardware, Infrastructure, and Security

The CCIN/PDC computer server and storage infrastructure, purchased in 2011 and installed in 2012, is very near 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 are also investigating cloud storage as an alternative to replacing hardware, although we have not yet found an appropriate option which meet the enterprise requirements of the PDC archive and CCIN system.

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 transitioned away from Oracle in 2017 to PostgreSQL, an open-source alternative to Oracle which is used by a majority of polar data centres around the world. The new PostgreSQL database was fully integrated into the PDC production system in April 2017, after extensive testing, with nearly flawless subsequent use.

New Partnerships and Support

Julie Friddell, previously the Manager and then Associate Director, became the Director of CCIN/PDC in March 2017. Through 2017, our small group lost two long-term staff and had three separate parental leaves. Throughout these changes, we have capitalized on our commitment to supporting our partners and driving forward the polar data community's national agenda for coordination and services. As a result, new collaborations have been formed with the Meteorological Service of Canada at ECCC, Amundsen Science, and Sentinelle Nord at l'Université Laval, and new discussions have begun with Québec Océan.

We are currently in the process of expanding the partnership and engagement for the Data Advisory Group (DAG, which comprises the partner Programs which use the Data Management Principles and Guidelines for Polar Research and Monitoring in Canada document for guiding their data management activities), which is currently made up of POLAR, NGMP, and NCP, to other programs, to help make requirements consistent within the community. The Principles and Guidelines document is currently being reviewed and updated, based on feedback received to date.

Following our 2016 entry into the World Data System of the International Council for Science (World Data Systems. (2017). Polar Data Catalogue is 100th Member of ICSU World Data System. Retrieved from http://www.icsu-wds.org/news/press-releases/polar-date-catalogue-is-100th-member-of-icsu-world-data-system), we are participating in a proposal to host the WDS Technology Office in Canada, along with the other two WDS members (Ocean Networks Canada and Canadian Astronomy Data Centre/Canadian Virtual Observatory). The mission would be to develop an interoperable Global Research Data Infrastructure to share WDS data and coordinate with the global research data community on policy, funding options, best practice, and standards. The office would open in 2018 and would be supported by Canada for at least three years. We have been talking with partners about collaborating on this project which would bring additional international resources, partners, and exposure to data management efforts in Canada.

Successful proposals to support and expand PDC and CCIN activities were prepared this year for the following organizations:

- NCP – for data management services
- NGMP - for data management services
- ECCC – to MSC and the Climate Research Division, to share Global Cryosphere Watch/ CRYONET and ECCC Arctic data via the PDC

Other proposals were prepared as follows (waiting to hear decisions on these):

- POLAR – for data management services
- CFI Cyberinfrastructure program - with CCADI, on data and metadata interoperability
- SSHRC Partnership program - with CCADI, on engaging and supporting northern Canadians in managing their data
- Amundsen Science - for data management services
- Compute Canada - for continuation of the offsite data backup that is currently in place
- Two additional NCE LOI applications in which CCIN/PDC was identified as potentially participating in data management activities

We have also engaged in discussions with Sentinelle Nord regarding managing their metadata and some of their data and have been invited to participate in a new network related to the Mackenzie Delta region. An additional LOI was prepared for an NSERC permafrost network which was unfortunately unsuccessful.

These activities have strengthened relations with many new and existing partners and will hopefully lead to more sustainable funding streams in the future. Sustainable funding to ensure the longevity of the support, services, and technical infrastructure we provide is a priority for CCIN, and expanding the scope of our work to complimentary fields, such as oceans, mountains, climate, and others is a strategy that has been suggested by the Polar Data Management Committee. The scalability and flexibility of our technical infrastructure allow such a change, thus we are exploring and considering our options for growing beyond the polar world in the future. If such a service could result from the support of ArcticNet over the last 15 years, that would be a very impressive legacy for ArcticNet to leave to Canada and the world.

Outreach, Communication, and Service

In 2017, CCIN began a newsletter to keep the polar data community apprised of announcements, events, and general news about our work. We have sent two emails to the list in the last six months and have had success engaging our community with announcements such as publishing the Data Management Principles and Guidelines for Polar Research and Monitoring in Canada.

Our social media presence on Twitter has increased with 420 followers, up from 334 last year, and we have made over 3,200 tweets total. Our Twitter and Facebook accounts are linked such that any tweets posted on Twitter are automatically posted on Facebook. The reach of our efforts is increasing, as evidenced by the increase in retweets and "likes," including by well-known organizations such as the World Data System and the Australian National Data Service (ANDS), of new metadata and data, news stories, and posts from conferences attended by CCIN staff. LinkedIn has become very active in the last year, as evidenced by our 395 connections, and the LinkedIn group we initiated, Polar Data in Canada, currently has 68 followers in only two months. We are exploring more extensive use of the new Polar Data in Canada community communication forum, so that it may truly act as a gathering place for people interested in polar data management.

In partnership with ECCC, 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 Polar Data Forum II. 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 was undertaken, and a presentation, including recommendations, was provided to ECCC in March 2017, with the final report being accepted in October. Results include requests for raw data (from researchers) plus interactive visualisations, maps, and graphs (mostly from decision makers), and users want real-time data as much as possible. Recommendations from these results are being used to inform changes to the CCIN website and expand activities with ECCC.

CCIN is in the process of drafting a chapter, entitled "Social Sciences Data Storage, Indigenous Knowledge, and the Polar Data Catalogue" in the esteemed handbook series, commonly referred to as The Arctic Book: The Routledge International Handbook of Library, Archival, Information, and Data Science for Arctic Social Sciences and Humanities. This chapter will cover an overview of why researchers should share social science data, why it is more difficult for Arctic social scientists to share data openly, a discussion of sensitive data, focusing largely on Indigenous Knowledge, and how PDC can help Northern communities build their own resources to fit their community needs. The book is due to be published in late 2018/early 2019.

CCIN/PDC purchased a booth for promotion at Arctic Change 2017 and engaged numerous individuals and organizations about the importance of data management, nationally and internationally. We provided interested parties with an attractive infographic with statistics on PDC data, metadata, and RADARSAT imagery; our four recent published articles; and a brochure highlighting CCIN/PDC and the services and support we provide to the community. We also collected contact information for people interested in our email newsletter, provided a T-shirt give-away to two lucky winners, and gave demonstrations for people interested in seeing the PDC in action.

In addition to the outreach activities listed in the Knowledge Mobilization section above, J. Friddell, CCIN Director, served in the following capacities: (1) Canadian representative, Arctic Data Committee of the International Arctic Science Committee and Sustaining Arctic Observing Networks; (2) Member, Canadian Tri-Agency Data Management Policy Advisory Committee; (3) Member, Canadian Committee on Antarctic Research; (4) Member, with G. Alix, of the Standing Committee on Antarctic Data Management of the Scientific Committee on Antarctic Research; (5) Representative to the Group on Earth Observations Cold Regions Initiative (GEOCRI); and (6) Member, Governing Body, Interdisciplinary Centre on Climate Change (IC3), University of Waterloo.

The Second Canadian Polar Data Workshop

With support from ArcticNet, POLAR, Natural Resources Canada, and various other sponsors, the Second Canadian Polar Data Workshop (CPDW) was held in Ottawa May 30-31, 2017. This was a follow-up to the highly successful first CPDW that occurred in May 2015. The objectives of the second workshop were 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 was structured to reach specific outcomes through working sessions and consensus building on themes of policy, funding, collaboration, and governance structure. In response to the feedback obtained from this workshop, CCIN coordinated the creation of the LinkedIn community forum, Polar Data in Canada, for the community to engage in informal discussions, planning, and announcements.

We intended for the discussion to be as inclusive as possible, and thus invited all rights holders and stakeholders interested in data management issues for the Arctic and Antarctic regions to participate. In this spirit, we are currently making plans to hold the next CPDW in the North, perhaps Inuvik, to encourage northern community members to participate more freely and openly. In the interim, next steps include completing a plan for forming a governance structure for Canada's polar data community, to facilitate collaboration and efficiency in the expanding community, as well as completing a position paper for circulation to decision makers, to advocate for increased support for data management in Canada.

Draft Strategic Plan for CCIN/PDC

Following brief discussion of this document at two Polar Data Management Committee (PDMC) meetings, CCIN is considering hosting a PDC Summit. The focus would be specifically on the PDC repository, the support and services we provide, and improvements and opportunities which the organization should act on. It was suggested at the December PDMC meeting that CCIN/PDC should undertake a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis with the Committee so that we can together identify the strategic objectives for the organization and plan activities for the next 5-10 years. CCIN/PDC is community driven, and we make it a priority to exceed expectations, so we look forward to the opportunity to understand how we may better meet community needs and requirements.

RESULTS

Since Feb 1, 2017, traffic on the PDC sites (PDC Search application, PDC Lite, and PDC Metadata/ Data Input) and the CCIN website included 28,042 visits, 19,201 unique visitors, and 46,289 page views. Since 1 January 2017, there have been 1,918 downloads of PDC datafiles, 316 downloads of Arctic RADARSAT images, and 45 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 many other countries.

Metadata and Data in the PDC

As of 29 January 2018, the number of PDC metadata records from all programs reached 2,817 with 55 in the SUBMITTED state, 9 in the SENTBACK state, 159 in the SAVED state, and 2,594 APPROVED and available publicly. This year, ArcticNet scientists and students have contributed 46 new metadata records, for a total of 1065 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: 112
- CBMP: 535
- IPY: 750
- CASES (Canadian Arctic Shelf Exchange Study): 89
- ADAPT (Arctic Development and Adaptation to Permafrost in Transition): 212
- NCP (INAC): 165
- BREA (INAC): 153
- APAN (Adaptation Program for Aboriginals and Northerners, INAC): 121
- NGMP (INAC): 50
- POLAR (Polar Knowledge Canada/CHARS): 82
- Reference (for other polar-related data and information portals and websites from around the world): 71

As of 29 January 2018, 379 datasets have been submitted to the PDC archive, 126 of which are affiliated with ArcticNet. Twelve of these ArcticNet datasets have been added this year, comprising 22,111 new data files. Of all the archived datasets in the PDC, 379 are available online, with the small remainder either not available publicly due to privacy issues, temporary embargoes, or ongoing efforts required to properly organize and archive the files. Since 29 January 2018, there have been 20 new metadata submitted by ArcticNet researchers which are currently under review. There were 16 DOIs added to ArcticNet datasets since 1 February 2017, resulting in 65 total ArcticNet DOIs, and 363 in the PDC. There are a total of 2,889,229 datafiles in the PDC, approximately 37 Terabytes in total, consisting of 21 TB of files from research datasets, 8.5 TB of RADARSAT imagery, and 7.2 TB of datafiles in our server which include a back-up of 1.7 TB for the Amundsen Science data, 2.5 TB of satellite images, and 3.2 TB of datasets which have been rescued. The satellite images and dataset to be rescued need to be processed, reviewed, and approved before they are available on the PDC. We undertake these data rescue activities when there is time available.

In addition to these concrete deliverables, the PDC is becoming increasingly recognized as a best practice for data management. For example, at the Canadian National Data Stewardship Framework Summit, hosted by Research Data Canada in late 2017, the PDC infrastructure and data management processes were highlighted as a successful implementation of effective data stewardship which should be used by others, including the Framework itself, to leverage our knowledge and experience.

DISCUSSION

The PDC has evolved 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 credibility and visibility, both nationally and internationally: CCIN/PDC expanded its partner programs and worked with partners to unify data management requirements and increase expectations for researchers to deposit data through the Data Management Principles and Guidelines for Polar Data Research and Monitoring in Canada and the Data Deposit Agreement document; CCIN/PDC was a key coordinator and contributor to the 2017 CPD Workshop, creating a community meeting space through the Polar Data in Canada LinkedIn group; and CCIN/PDC, in partnership with Ocean Networks Canada and the Canadian Astronomy Data Centre/ Canadian Virtual Observatory, is participating in a proposal to host the WDS International Technology Office in Canada. These activities underscore the PDC's and CCIN's reputation as a reliable, trustworthy, and professional partner in polar data management in Canada. Other achievements highlight CCIN/ PDC efforts to remain relevant and up-to-date with technology: release of a new open-source database which extends flexibility of the PDC technical platform, launch of a modernized CCIN education/ information website, improvement of the PDC Metadata/Data Input application and the PDC Help Manual which helps people make better use of our online services, and development of a new PDC Search application with new interface and features.

As 2017-2018 is the last year of funding for ArcticNet research projects, a Call for Data letter was circulated to ArcticNet NIs in December 2017 by ArcticNet management, with required deposit of ArcticNet data, either in the PDC or other acceptable repository, by June 2018. The legacy of these important data depends on researchers' cooperation and participation, thus we are gearing up for the increased workload expected to accompany this final push for data in the spring and summer of 2018.

Discussions continue with a growing number of organizations regarding collaborating on polar data management efforts and serving new groups' data stewardship needs. We also continue to seek financial support for replacing our server hardware system, which is nearing its end of life, and are investigating a cloud-based storage solution at l'Université Laval as an option. Such hardware and accompanying support are critical for sustaining the PDC as it continues to take on larger roles as a nationally and internationally recognized data repository.

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, strengthens effective management of Arctic and Antarctic data in Canada and provides the ability to build and maintain a capable and respected archive for long-term access to 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 secure 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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REFERENCES

Anonymous. (2009). Data's shameful neglect. Nature, 461(7261), DOI:10.1038/461145a.

ENSERINK, M. (2016). IN DRAMATIC STATEMENT, EUROPEAN LEADERS CALL FOR "IMMEDIATE" OPEN access to all scientific papers by 2020. Science, DOI: 10.1126/science. aag0577.

International Council for Science (ICSU). (2014). Press release: International Council for Science endorses open access to scientific record; cautions against misuse of metrics. Retrieved January 16, 2016 from: http://www.icsu.org/general-assembly/31st-general-assembly-auckland-2014/news/press-release-2013-international-council-for-science-endorses-open-access-to-scientific-record-cautions-against-misuse-of-metrics.

Parsons, M., Godøy, Ø., LeDrew, E., de Bruin, T., Danis, B., Tomlinson, S., & Carlson, D. (2011). Managing very diverse data for complex, interdisciplinary science. Journal of Information Science, pp. 1-21. DOI: 10.1177/0165551511412705.

PUBLICATIONS

Church, D., J. Friddell, and E. LeDrew, 2017, The Northern Voice: Listening to Indigenous and Northern Perspectives on Management of Data in Canada, Data Science Journal 16, p. 48. Published online: http://doi.org/10.5334/dsj-2017-048.

Church, D., J. Friddell, and B. Mills, 2017, Polar Data Catalogue, in Navigating Weather, Water, Ice and Climate Information for Safe Polar Mobilities. World Weather Research Program, World Meteorological Organization. Published online: http://www.polarprediction.net/fileadmin/user_upload/www.polarprediction.net/Home/Organization/Task_Teams/PPP-SERA/WWRP_PPP_No_5_2017_11_OCT.pdf

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