ArcticNet ᐅᑭᐅᖅᑕᖅᑐᕐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ

Impacts of Environmental Change in the Canadian Coastal Arctic

A Compendium of Research Conducted during ArcticNet Phase IV (2015–16)

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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 ᑐᑭᓯᓂᐊᖃᑎᒌᑦ ᐃᓂᖃᖅᑎᑕᐅᔪᖅ ᓚᕞ, ᑯᐸᒃ ᓯᑎ, ᑲᓇᑕ

ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ ᐱᑕᖃᕈᓐᓇᖅᑎᑕᐅᔪᖅ ᑖᒃᑯᓐᓇᖕᒐᑦ ᑮᓇᐅᔭᒃᓴᖅᑲᖅᑎᑕᐅᓪᓗᓂ ᑐᑭᓯᒐᓱᐊᖃᑎᒌᑦ ᐱᑐᒃᓯᒪᓂᒃᑯᑦ ᑐᑭᓯᓐᓂᐊᖃᑎᒌᑦ ᐱᐅᓛᑦ ᑲᓇᑕᒥ, ᑲᑐᑎᔭᐅᓪᓗᓂ ᐱᓕᕆᐊᕆᔭᐅᔪᖅ ᑖᒃᑯᓐᓇᖕᒐᑦ ᓄᓇᒥᐅᑕᕐᓂᒃ ᖃᐅᔨᓴᐃᔨᒻᒪᕆᑦ ᐊᒻᒪᓗ ᐃᑯ-ᒪᓕᕆᓂᕐᒥ ᖃᐅᔨᓴᖅᑎᑦ ᑲᑎᒪᔩᙱᑦ, ᑲᓇᑕᒥ ᐃᓕᓐᓂᐊᕐᕕᒃ ᐃᓘᓯᓕᕆᓂᕐᒥ ᖃᐅᔨᓴᐃᓂᖅ, ᐃᓅᓯᕐᒥ ᖃᐅᔨᓴᐃᓂᒻᒪᕆᒃ ᐊᒻᒪᓗ ᐃᓅᔾᔪᑎᒋᔭᓐᓇᖅᑕᑦᑎᒍᑦ ᖃᐅᔨᓴᐃᓂᖅ ᑲᑎᒪᔩᙱᑦ, ᐊᒻᒪᓗ ᐱᓇᓱᐊᖅᑐᓕᕆᓂᖅ ᑲᓇᑕ.

ᐅᑯᐊ ᐱᑐᒃᓯᒪᕝᕕᑦ ᐱᐅᓛᑦ ᑲᓇᑕᒥ ᐊᔾᔨᐅᖕᒋᑑᔪᒥᒃ ᐱᓇᓱᐊᖃᑎᒋᔭᖕᒐᑦ ᐊᕙᑖᓂᑦ ᐃᓕᓐᓂᐊᕐᕕᒃᔪᐊᓂ, ᐱᓇᓱᐊᖅᑐᓕᕆᓂᖅ ᑲᓇᑕ, ᒐᕙᒪᒃᑯᑦ ᐊᒻᒪᓗ ᑮᓇᐅᔭᓕᐅᕆᓯᐊᕆᑎᒃ ᐊᐅᓚᑦᓯᔨᐅᔪᑦ ᑐᕌᖅᑐᑦ ᑐᓄᑎᒍᓐᓇᖅᓗᒍ ᑲᓇᑕᒥᐅᑦ ᖃᐅᔨᓴᖅᓂᖕᒐᑦ ᐊᒻᒪ ᓇᖕᒥᓂᖃᖅᑐᓕᕆᓂᖅ ᐱᓕᕆᔪᓐᓇᑦᓯᐊᖅᑐᑦ ᑕᒪᑐᒧᖕᒐ ᒪᑭᑕᓇᓱᐊᕐᓂᕐᒧᑦ ᐊᒻᒪᓗ ᐃᓅᓯᕐᒥ ᐃᑲᔫᑎᓂᐊᖅᑐᓄᑦ ᑕᒪᐃᓐᓄᑦ ᑲᓇᑕᒥᐅᓄᑦ. ᑕᐃᒪᓗ ᐃᓗᓪᓕᕆᓗᐋᖅᑕᖓ ᐃᓚᖓ ᒐᕙᒪᒃᑯᑦ ᓄᑖᓂᒃ ᐱᒥᐊᓪᓚᒍᑎᓕᕆᓂᖅ ᐋᖅᑭᒃᓯᒪᐅᑎᖓᑦ, ᐅᑯᐊ ᑲᓇᑕᓕᒫᒧᑦ, ᐊᒥᓱᑦ ᐃᓂᖅᑎᕆᔪᓐᓇᖅᑐᑦ ᐊᒻᒪᓗ ᐊᒥᓱᑦ ᖃᓄᑐᐃᓐᓇᖅ ᐱᓕᕆᔪᓐᓇᖅᑕᓖᑦ ᑲᑎᖕᒐᔪᑦ ᐱᐅᓂᕐᓵᖕᒍᔪᒥᒃ ᖃᐅᔨᓴᐃᓂᕐᒥᒃ ᐱᓇᓱᐊᖅᑐᓕᕆᓂᕐᒥ ᖃᐅᔨᓴᖅᑕᐅᓕᕈᓐᓇᖅᑐᓂᒃ ᐊᒻᒪᓗ ᐋᖅᑭᒃᓯᒪᐅᑎᖓᑦ ᖃᑭᒐᓯᐊᕈᑎᒋᔭᐅᖅᑐᓂᒃ.

ᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ ᐱᑐᒃᓯᒪᖃᑎᒋᔭᖕᒋᑦ ᑖᒃᑯᓐᓇᖕᒐᑦ ᑐᑭᓯᒐᓱᐊᖃᑎᒌᑦ ᐱᑐᒃᓯᒪᓂᒃᑯᑦ ᐱᐅᓈᑦ ᑲᓇᑕᒥ ᑎᒥᖕᒍᖅᑎᑕᐅᓯᒪᔪᑦ ᑮᓇᐅᔭᓕᐅᖅᑎᐅᓚᓯᐊᕆᑎᒃ ᑯᐊᐳᓴᓐ ᐊᑖᒍᑦ ᐊᑎᖅᑲᖅᓗᑎᒃ "ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖃᑎᒥᒌᑦ ᑎᒥᖓ" ᑕᐃᑲᓂ ᑎᓯᐱᕆ 2003.

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

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

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

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

Canada

Coming together in the study of a changing Canadian Arctic.

ᐊᐅᓪᓚᖃᑎᒌᒃᓯᒪᔪᑦ ᐃᓕᑦᑎᓇᓱᖃᑎᒌᒃᑐᒡᔪᑎᒃ ᐊᓯᑦᔨᕐᐸᓪᓕᐊᓂᖓᓂᒃ ᑲᓇᑕᐅᑉ ᐅᑭᐅᖅᑕᖅᑐᖓ.

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

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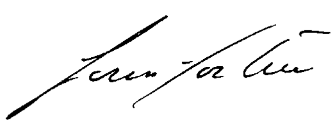
FOREWORD

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 first year of Phase IV (2015-2016) of ArcticNet. We thank all of our network investigators, students, other researchers, colleagues and partners for helping ArcticNet attain its goals, and the ArcticNet compendium editorial team for bringing this document through to completion.

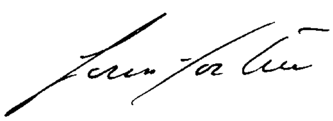
Louis Fortier, Scientific Director of ArcticNet



ᐱᒋᐊᕐᓂᖓ

ᐅᓇ ᐅᑭᐅᖅᑕᖅᑐᖅ ᓄᓇᖓ ᓄᓇᕐᔪᐊᒥ ᐊᒃᑐᖅᑕᐅᖄᕐᓂᐊᖅᑐᖅ ᐊᒻᒪᓗ ᐊᖏᓛᖑᔪᒥᒃ ᓱᑯᑕᐅᓗᓂ ᑕᒪᑐᒪᖔᑦ ᓂᒋᐊᓂᑲᖅᑐᓂᑦ ᐅᖅᑰᓯᕙᓪᓕᐊᓂᖔᓄᑦ ᓄᓇᕐᔪᐊᑦ. ᐅᓄᖅᑐᑦ ᑕᒪᔾᔭᐅᓕᖅᑐᑦ ᖃᐅᔨᑎᑦᑎᔪᑦ ᐅᑭᐅᖅᑕᖅᑐᖅ ᐅᖂᓯᓂᖔᓄᑦ ᖃᐅᔾᔭᐅᔪᑎᖃᖅᓱᑎᒃ ᓯᓚᐅᑉ ᖃᓄᐃᓐᓂᖓᓂᒃ ᓴᓇᕿᑕᐅᔪᓂᒃ ᓇ, ᓇᐃᖅᑐᖅ ᑕᑯᔭᐅᔪᖅ ᓄᓇᑐᐃᓐᓇᒥ, ᑕᓇᐅᕐᒥ ᐊᒻᒪᓗ ᓄᓇᕐᔪᐊ ᓯᓚᑖᓂ. ᓇᐃᓈᖅᓗᒍ ᐅᖃᕈᓐᓇᖅᑐᒍᑦ ᐅᑭᐅᖅᑕᖅᑐᖅ ᓯᓚᖓᑕ ᐊᕙᑎᖓᑕ ᐊᓯᑦᔩᕐᓂᖓ ᐊᒃᑐᖅᑕᐅᓂᖓᓂᒃ ᓱᕐᑯᐃᖅᑕᐅᓇᓱᒃᓯᒪᔪᓂᑦ 2004, ᐊᒥᓱᑦ ᐊᔾᔨᒌᙱᑦᑐᑦ ᓯᓚᓐᓂᐊᖅᑐᑦ, ᐃᓅᓯᓕᕆᓂᕐᒥᒃ ᑮᓇᐅᔭᑎᒍᑦ ᐱᕙᓪᓕᐊᓂᖅ ᐊᒻᒪᓗ ᓄᓇᖏᓐᓄᑦ ᒐᕙᒪᓕᕆᓂᖅ ᑕᒪᔾᔭ ᐱᓕᕆᔭᐅᔪᑦ ᐅᑭᐅᖅᑕᖅᑐᒥ ᑕᐃᒪᓗ ᐊᓯᑦᔫᓂᐊᖅᑐᖅ ᑭᓱᖑᕐᓗᓂ ᐅᑎᕈᓐᓇᕐᓂᐊᙱᑦᑐᖅ ᐅᑭᐅᖅᑕᖅᑐᒥ ᑕᐃᒪᓐᓇᐅᖏᓐᓇᐅᔭᓕᕐᓂᐊᖅᑐᑦ. ᐅᑭᐅᖅᑕᖅᑐᒥ ᑐᑭᓯᓐᓂᐊᖅᑲᑎᒌᑦ ᓄᐊᑎᓇᔪᑦ ᖃᐅᔨᒪᔭᐅᔪᓂᒃ ᐊᒻᒪᓗ ᓱᕐᑯᐃᖅᑕᐅᓯᒪᔪᓂᒃ ᑭᖕᖑᒪᒋᔭᐅᓯᒪᔪᓂᒃ ᐋᕿᒃᓯᓂᐊᕐᓗᑎᒃ ᓱᖏᐅᑎᑦᑎᔾᔪᑎᒃᓴᐃᑦ ᐊᒻᒪᓗ ᐊᑐᐊᒐᐃᑦ ᐅᑯᐊ ᐃᑲᔪᕐᓂᐊᖅᑐᖅ ᐅᑭᐅᖅᑕᖅᑐᒥᐅᓂᒃ ᐊᒻᒪᓗ ᑲᒻᐸᓂᐅᔪᓂᒃ ᐱᓂᒃᓴᕙᖀᖅᓯᒪᓗᑎᒃ ᐊᒃᑐᖅᑕᐅᓂᖓᕐᓂᖓᓄᑦ ᐊᕙᑎᖓᑦ ᐊᒻᒪᓗ ᐃᓅᓯᖏᑦ ᐊᓯᑦᔩᕐᓗᑎᒃ ᓯᒡᔭᖏᑦ ᑲᓇᑕᐅᑉ ᐅᑭᐅᖅᑕᖅᑐᐊᓂ. ᐅᓇ ᑕᐅᑦᑐᓇᔭᕗᑦ ᓴᓇᓗᒍ ᓯᕗᓂᒃᓴᕗᑦ, ᖁᔭᓐᓇᒦᒃ ᑕᒪᔾᔭᐅᖕᒪᑦ ᑐᓴᐅᒪᖃᑎᒌᖕᓂᖅ ᖃᐅᔨᒪᖃᑎᒌᖕᓂᖅ, ᒥᐊᓂᕆᓂᖅ, ᐋᕿᒃᓱᐃᓂᖅ ᐊᒻᒪᓗ ᐃᓗᓪᓕᖅᓯᐃᓂᖅ, ᖃᐅᔨᓴᖅᑎᒻᒪᕇᑦ ᐊᒻᒪᓗ ᐅᑭᐅᖅᑕᖅᑐᒥᐅᑦ ᑲᑎᓯᒪᔭᖏᓐᓂᑦ ᐱᓕᕆᑦᑎᐊᖅᓗᒋᑦ ᐱᐅᙱᑦᑐᑎᒃ ᐊᒃᑐᐃᓇᔭᓚᐅᖅᑐᓄᑦ ᐊᒻᒪᓗ ᐊᖏᒡᓕᑎᓯᒪᑦᑐᒋᑦ ᐱᐅᔪᓂᒃ ᐊᑑᑎᖃᑦᑎᐊᖅᑐᓂᒃ ᐱᑦᑐᒍ ᑕᒪᓇ ᐊᓯᑦᔩᕐᓂᖅ. ᑭᓲᓂᖏᑦ ᐱᑕᖃᖅᑐᑦ ᐅᑯᐊ ᓯᕗᓪᓕᕐᕚᑦ ᐱᓕᕆᔭᐅᔪᑦ ᑕᒪᑐᒧᖓ ᑕᕐᑯᔭᐅᓯᒪᔪᓂᑦ ᑲᔪᓯᑦᑎᐊᖅᓯᒪᔪᑦ ᓯᕗᓪᓕᕐᓂ ᐊᕐᕿᒍᓂ ᑎᓴᒪᓂ (ᓱᕐᕿᓂᖓ 1) ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓐᓂᐊᖅᑲᑎᒌᑦ. ᖁᔭᓐᓇᒦᒃ ᑕᒪᑦᓯ ᑐᑭᓯᓇᓱᐊᖅᑲᑎᒌᑦ ᖃᐅᔨᓴᖅᑎᑦ, ᐃᓕᓐᓂᐊᖅᑐᑦ, ᐊᓯᖏᓪᓗ ᖃᐅᔨᓴᖅᑎᑦ, ᓴᓇᖅᑲᑎᒋᔭᕗᑦ ᐊᒻᒪᓗ ᐱᓇᓱᐊᖅᑲᑎᒋᔭᕗᑦ ᐃᑲᔪᖅᑐᑦ ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓐᓂᐊᖅᑲᑎᒌᒃᑯᓄᑦ ᑲᔪᓯᑦᑎᐊᖅᑎᓪᓗᒋᑦ, ᐊᒻᒪᓗ ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓐᓂᐊᖅᑲᑎᒌᑦ ᑭᓲᓂᖏᓐᓂᒃ ᑎᑎᕋᖅᑎᖏᑦ ᐱᓇᓱᐊᖅᑲᑎᒌᓪᓚᐅᖅᑐᑦ ᐅᓇ ᑎᑎᕋᖅᓯᒪᔪᖅ ᐱᔭᕇᑦᑎᐊᕋᓱᓪᓗᒍ.

ᐃᓕᓴᐃᔩᒻᒪᕆᒃ ᓗᐃ 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 première année (2015-2016) des projets de recherche de la phase IV d'ArcticNet (2015-2018). Nous remercions tous les chercheurs principaux, étudiants, autres chercheurs, collègues et partenaires d'ArcticNet pour leur contribution aux nombreux et rapides succès du Réseau, de même que l'équipe éditoriale de ce compendium pour en avoir assuré la réalisation.

Louis Fortier, directeur scientifique d'ArcticNet

INTRODUCTION

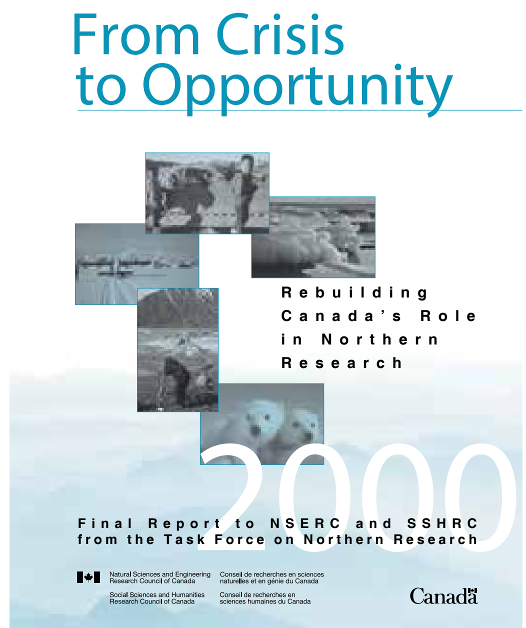
ArcticNet Compendium Editorial Team

Mickaël Lemay, Ashley Gaden, Carl Barrette

This Compendium of Research (2015-16) presents research progress of the first year of Phase IV ArcticNet projects, which ran from 1 April 2015 to 31 March 2016. The ArcticNet research program was developed and oriented toward its main mission, namely "To bring together Canadian and foreign Arctic expertise to conduct Integrated Regional Impact Studies (IRIS) of the consequences of climate warming, environmental changes and societal changes in key areas of the coastal Canadian Arctic". ArcticNet Phase IV was organized under five complementary research themes: 1) Marine systems (16 projects); 2) Terrestrial systems (10 projects); 3) Inuit health, education and adaptation (8 projects); 4) Northern policy and development (3 projects); and 5) Knowledge transfer (4 projects).

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

'FROM CRISIS TO OPPORTUNITY' AND THE IMPACT OF ARCTICNET



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In 2000, the seminal report of the NSERC/SSHRC Task Force on Northern Research (Hutchinson et al., 2000), the report demanded the creation of a Network of Centres of Excellence focusing on the Arctic with greater access to Canadian Coast Guard icebreakers for research. In 2003-2004, by implementing most of the Report's recommendations, the ArcticNet NCE, supported by its main core infrastructure the scientific icebreaker CCGS *Amundsen*, jump-started a spectacular revitalization of Canada's research effort in the North. No other initiative has had a larger impact in transforming modern Canadian Arctic research (Hik, 2010), in integrating its different forces, and orienting it towards answering the needs of stakeholders and the formulation of policy.

As ArcticNet enters its final phase of NCE funding, we can look back over the tremendous accomplishments of the Network to date.

Since 2004, ArcticNet has:

- Formed one of the most dynamic network of Arctic experts in the world;
- Involved Inuit at all levels of the Network from fieldwork to the Board of Directors;

- Created unprecedented synergy among the natural, social and health sciences;
- Leveraged its NCE core funding by a factor of 3 to 5 depending on year;
- Mobilized and successfully deployed Canada's only dedicated research icebreaker;
- Provided its researchers with improved access to the services of the PCSP;
- Trained almost 1,300 graduate students and postdoctoral fellows (56.3% female);
- Helped establish over 85 Arctic specialists in universities and government departments;
- Supported 29 new research chairs including two Canada Excellence Research Chairs;
- Managed over 22 ArcticNet and non-ArcticNet major programs on the Amundsen;
- Established significant science collaborations with 11 countries;
- Delivered nine of the Canadian IPY programs including the two largest in the world;
- Partnered with the private sector in several multi-million dollar research programs;
- Conducted Inuit health surveys in 48 of the51 communities of the Canadian Arctic;
- Delivered 47 projects directly supporting Inuit adaptation, health & well-being and education;
- Contributed vastly to Canadian and International Regional assessments (Beaufort & AMAP);
- Implemented Integrated Regional Impact Studies (IRIS) in four regions of the Arctic;
- Coordinated the ArcticNet Scientific Meeting (ASM), Canada's annual Arctic conference;
- Organized two editions of the international Arctic Change Conference;
- Played a pivotal role in the organization of the IPY closing conference in 2012;
- Developed and supported the successful Polar Data Catalogue (PDC);
- Engaged policy makers and stakeholders through the IRIS process and the ASM;
- Obtained major philanthropic support for northern research and capacity building;
- Attracted the $3M annual Arctic Inspiration Prize in support of northern initiatives;
- Fostered Sentinel North, a major R&D effort to bring new technologies in the North;
- Reached out to the general public to bolster Canada's Arctic dimension;
- Helped bring Arctic issues to the forefront of political agendas in Canada and abroad.

Louis Fortier

Scientific Director

Leah Braithwaite

Executive Director

References

Hik, D. 2010. A northern science policy for Canada. 2030 North National Planning Conference. Session Paper No. 4.

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

SECTION I. MARINE SYSTEMS

Section I is composed of 16 ArcticNet research projects covering biological, ecological, biogeochemical and physical components of the Canadian Arctic marine systems.

Hidden Biodiversity and Vulnerability of Hard-Bottom and Surrounding Environments in the Canadian Arctic

Project Leaders

Philippe Archambault (Université du Québec à Rimouski); Evan Edinger (Memorial University of Newfoundland)

Network Investigators

Suzanne Dufour (Memorial University of Newfoundland)
Louis Fortier (Université Laval)
Kevin Hedges (Fisheries and Oceans Canada - Central & Arctic Region)
Kim Juniper (University of Victoria)
Sally Leys (University of Alberta)
Connie Lovejoy (Université Laval)
Christian Nozais (Université du Québec à Rimouski)
Paul Snelgrove (Memorial University of Newfoundland)

Collaborators

Calvin Campbell (Dalhousie University)
Laurent Chauvaud (Université de Bretagne Occidentale)
Pierre Galand (Observatoire Oceanologique de Banyuls-CNRS)
Kent Gilkinson (Fisheries and Oceans Canada - Northwest Atlantic Fisheries Centre)
Scott Grant (Fisheries and Marine Institute of Memorial University of Newfoundland)
Edward King (Government of Canada - Geological Survey of Canada)
Guillaume Massé (University of Plymouth)
Frédéric Olivier (National Museum of Natural History of France)
Tim Siferd (Fisheries and Oceans Canada - Freshwater Institute)
Kapil Tahlan (Memorial University of Newfoundland)
Margaret Treble (Fisheries and Oceans Canada - Freshwater Institute)
Réjean Tremblay (Institut des sciences de la mer de Rimouski, UQAR)
Vonda Wareham (Fisheries and Oceans Canada - Northwest Atlantic Fisheries Centre)
Ursula Witte (University of Aberdeen)

HQP

Barbara de Moura Neves, Doctoral Student (Memorial University of Newfoundland)
Growth rates and patterns in deep-water corals (Cnidaria, Anthozoa) in relation to environmental variables.
Marie Pierrejean, Doctoral Student (--)
Rebecca Steinhart, Doctoral Student (Memorial University of Newfoundland)
Joost Verhoeven, Doctoral Student (Memorial University of Newfoundland)
Vincent Carrier, Masters Student (UNIS - The University Centre in Svalbard)
Biogeography of marine pico- and nanoeukaryotes around Svalbard Archipelago, Norway
Curtis Dinn, Masters Student (University of Alberta)
Sponges of the Canadian Arctic
Julie-Anne Dorval, Masters Student (Université du Québec à Rimouski)
Dimitri Kalenitchenko, Post-Doctoral Fellow (Université Laval)
Cindy Grant, Research Associate (Université du Québec à Rimouski)
Marianne Potvin, Research Associate (Université Laval)
Mary Thaler, Research Associate (Université Laval)
Keith Jackson, Technical Staff (University of Aberdeen)

ABSTRACT

Polar ecosystems are experiencing major stresses. Potential impacts of these stressors on benthic ecosystems in the Arctic are still difficult to assess because of the lack of baseline data and incomplete sampling. Hard-bottom and surrounding environments represent the most seriously under-sampled habitats. Hard substrate habitats host a distinct fauna of invertebrates and fishes, some of which are highly vulnerable to damage from bottom-contact fishing gear. This project will investigate biodiversity from microbes to fishes, in the steep-and-deep marine habitats of the Canadian Arctic. The specific objectives are to: i) describe the biodiversity and functional role of hard-bottom seafloors including coral and sponge areas, and other fauna living in the surrounding areas; ii) describe cryptic and microbial diversity associated with biogenic habitat-forming species; iii) describe microbial communities, to link them with biogeochemical processes and symbiotic relationships; iv) identify environmental drivers of associated fish species, and; v) explore whether Arctic cod adopt a demersal distribution in summer. These objectives will be achieved with Remotely Operating Vehicle based sampling. Overall, this project will bring new knowledge about the biology of Arctic hard-bottom seafloors, and will help project partners monitor and conserve Arctic biodiversity in the face of the challenges of environmental change.

KEY MESSAGES

- Project kick off workshop including videoconference meeting to finalise management structures and detail of schedule (May 2015).
- Engineering development and sea trials for a sample elevator (May – June 2015).
- Participate in ArcticNet 2015 cruises in the Baffin Bay region and in the Archipelago region.
- Successful deployment of SuperMohawk ROV (SuMo) and dives for 19 hours and 31 minutes. The number of hours under water showed a clear improvement from past experience.
- Successful deployment of sampling elevator to enhance ROV capabilities.
- Successfully collection of sponges and deep-water coral to study associated organisms.
- Exposure of a new team of benthic and ROV researchers to Arctic research.
- Characterization of multiple habitats through video transects, especially habitat that could not be samples otherwise than with an ROV.
- Participate in Schools on Board.
- Participate in the Annual Circumpolar monitoring Biodiversity Program.
- Participate in ArcticNet annual meeting, international conferences, and workshops.

OBJECTIVES

The objectives of this project are to:

1. describe the biodiversity and functional role and the level of uniqueness of inaccessible habitats of hard-bottom seafloors including coral and sponge areas;
2. describe cryptic and microbial diversity associated with biogenic habitat-forming species;
3. compare microbial communities from RNA and DNA, to link communities' with biogeochemical processes and symbiotic relationships;
4. investigate the influence of cold-water corals on the diversity and composition of meiofauna/megafauna living in the surrounding soft-bottom sediments;

5. identify environmental drivers of biotic communities in hard bottom habitats, including associated fish species; and,
6. explore if Arctic cod adopt a demersal distribution hugging the seafloor in July during maximum irradiance and minimum ice cover.

Specific objectives for 2015 were to:

1. determine which invertebrate and fish species are present in the various sites;
2. determine how different steep/deep areas are from gravelly bottom sites described in Roy et al. (2014);
3. measure the size-frequency distribution of cold-water corals especially the prominent and common Arctic sea pen *Umbellula encrinus*, and of the most prominent sponge species occurring at the various sites;
4. sample corals and sponges in order to assess their associated microbial and invertebrate faunas, and sampling for verifying identification of sponges. Specifically, to sample carnivorous sponges (*Cladorhiza* and *Chondrocladia*) from the Scott Inlet ROV dive site (and opportunistically from other locations) to determine their species identity and perform a metagenomic analysis of the microbial communities associated with various morphological features of these unique sponges; and,
5. take box core samples from most of the dive sites to describe resident microbial communities using metagenomic approaches and culture Actinobacteria, which are known antibiotics producers (this research will be done in collaboration with Dr. Kapil Tahlan at Memorial University).

All these objectives are underway as the samples arrived in specific lab a few weeks after the demobilisation of the CCGS *Amundsen* (November 1-7, 2015).

INTRODUCTION

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

Diversity of cold-water corals is thought to decrease northward and westward into the Arctic (Kenchington et al. 2010, 2011). Bycatch records indicate relatively high diversity of sea pens and soft corals, relatively low diversity of gorgonians, and unresolved diversity of black corals in Baffin Bay (Kenchington et al. 2010), with these estimates largely matched by *in-situ* observations of corals during 2013 and 2014 *Amundsen* ROV expeditions (Neves et al. in review, Neves et al. ASM 2014 talk). Sponge bycatch has been quantified, but sponge diversity remains poorly known, because of limited targeted sampling efforts, lack of readily available ID guides, and minimal attention from taxonomists (Kenchington et al. 2010). Initial sampling in 2014 recorded several first records of sponge species in Baffin Bay previously known from boreal waters elsewhere in the North Atlantic and South Atlantic. Unfortunately, the megafauna, meiofauna, and microbiota associated with these sponges and corals could not be studied due to limitations to the sampling capabilities of the SuperMohawk ROV (SuMo) that we address through this proposal (construction of an elevator system to transport samples in collaboration with the Canadian Scientific Submersible Facility (CSSF)).

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

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

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

Acoustic data of fish distribution and abundance validated by trawls have been accumulated since 2003. Our recent synthesis of this information indicates that Arctic cod (*Boreogadus saida*) is by far (95%) the dominant pelagic fish in the Canadian Arctic (Fortier pers com). Starting in January, Arctic cod distribute over progressively deeper grounds as light and their vulnerability to surface-dwelling predators (seals, seabirds) increase over the winter. In Julym, wth maximum light and minimum ice, Arctic cod disappear from the water column, suggesting a demersal distribution that hides the fish from sonar detection. The ROV will enable us to test this hypothesis by direct observation of fish distributions immediately above and on the bottom.

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

ACTIVITIES

1. Dissemination of scientific results

- Dissemination of results to the scientific communities, public, partners and stakeholders through high-ranking articles, either submitted (2), accepted or published (1) and book chapters (3).
- Dissemination of scientific results via oral presentations (7) during national/international conference: AGU-GAC-MAC-CGU Joint Assembly (Montreal, QC, Canada, May 2015), Canadian Quaternary Association biennial meeting (St. John's, NL, Canada, August 2015), First International Carbonate Mound Conference (Monte Veritá, Ticino, Switzerland, November

2015), Benthic Ecology Meeting (Portland, USA, March 2016).

- Participation in workshops: Expert Network State of the Arctic Marine Biodiversity Report (SAMBR) Writing Workshop of the CircumpolarBiodiversity Monitoring program (CBMP), CAFF Secretariat in Iceland (April 14-16, 2015); Analysis of Metagenomic Data workshop in Halifax (June 24-26, 2015); Adaptation Actions for a Changing Arctic Baffin Bay & Davis Strait Regional Assessment in Danemark (June 9-11, 2015).
- Inclusion of ArcticNet imagery in a review paper submitted to Prog. Oceanogr. (Lllovet et al.) and in a presentation on Canadian Marine Biodiversity (Snelgrove's Canada Oceans Lecture - Marine Biodiversity and the Health of Canada's Oceans).

2. HQP training

- New MSc students started in 2015-2016: Vincent Carrier (May 2015), and Curtis Dinn (January 2016).
- New PhD students started in 2015-2015: Rebecca Steinhart (April 2015) and Joost Verhoeven (April 2015).
- New Postdocoral Fellow started in 2015-2016: Dimitri Kalenitchenkor (October 2015).
- New PhD student Marie Pierrejean will start as soon as her Visa will be approved. This delay was not anticipated.

3. Field work in the Canadian Arctic

- Joint ArcticNet cruise on the CCGS *Amundsen* (P. Archambault, S. Dufour, C. Grant, K. Jackson, D. Kalenitchenko, B. de Moura Neves, C. Nozais, F. Olivier, P. Snelgrove, R. Steinhart, J. Verhoeven, V. Wareham).
- Five locations in Baffin Bay were surveyed using the SuMo ROV during the CCGS *Amundsen* 2015 expedition: Navy Board Inlet, Scott Inlet, Cape Dyer, Qikiqtarjuaq, and Frobisher Bay. The primary activity was the acquisition of HD video data for more than 19 h of video.
- An elevator built to be used with this ROV was deployed in Scott Inlet where sampling of sponges and cold water corals was collected.
- A multibeam survey was conducted in the Qikiqtarjuaq (2.5 hours) and in the Cape Dyer (5 hours) dive sites, from where multibeam data was not previously available.
- Twenty sediment samples were collected from box cores for microbial community analyses.
- A lander was deployed at station 177 on 20th Oct 2015. The lander is equipped with a HD camera and will take pictures of the seafloor for a year, every hour for a total of 8640 pictures. This lander deployment is a collaboration with Prof. U. Witte from University of Aberdeen in Scotland.
- Sediment incubations have been done at two stations to study biogeochemical nutrient fluxes at the interface sediment-water colum. These incubations will help to understand the functioning of the ecosystem in areas of hidden biodiversity.
- Samples have been collected at eight stations to study endobenthos diversity, organic matter content, and prokaryotic abundance.
- We have been compiling background data on corals, sponges, and hard-bottom environments throughout the Canadian Arctic, but emphasizing the Eastern Arctic. These efforts include making a single GIS project with all the ArcticNet bathymetry, CTD data, relevant sub-bottom profile data, and coral, sponge and other large structure-forming megafauna bycatch data for the Canadian Arctic. We will add to this data on the distribution of fishing effort when these data become available.
- We also quantify seasonal variations in benthic faunal abundance and diversity and behaviour, at a high temporal resolution, using the Ocean Networks Canada seafloor cabled observatory

located at 6-meter of water depth, in Cambridge Bay, Nunavut. Faunal composition and abundance were determined using an underwater HD video camera mounted on the instrument platform. The camera acquired 5-minute videos of the seabed at 2-hour intervals for more than 2 years. The image analyses performed are similar to the one need to analyses lander operation at station 177 and ROV HD video described earlier.

- Planning meetings and preparation for the ArcticNet cruises in 2016.

4. Field work in the context of international collaborations

- We have been invited by the British Antarctic Survey (Dr H. Griffith) to participate in February 2016 to an expedition in Antarctica as part of the research and monitoring required by CCAMLR to inform and support the management of Marine Protected Areas (CM 91-04) South Orkney Islands. Because the lack of funding and the timing to follow the security courses required to be onboard the *RRS James Clark Ross* (Elementary Safety at Sea-Secourisme élémentaire en mer – 165$ – http://www.imq.qc.ca/formation-continue/003-fum-72.php) and the 60h basic safety STCW-BS (http://www.imq.qc.ca/formation-continue/015-fum-03.php) which is at St-Romulad (QC) for 1,370$ + accommodation and per diem), we will not be able to participate. However, we are still networking with this group for collaboration in the field during this 2016 cruise and also during the potential program Antarctic Circumnavigation Expedition ("ACE") in 2017.

5. Laboratory work, instrumentation, analysis

- MSc student Julie-Anne Dorval went to University of Victoria for an internship to develop image analysis protocole .
- MSc student Curtis Dinn is making spicule preparations from two sponges to attempt to ID the species, and potentially extracting 18sDNA for taxonomic identification. He is analysing the video to determine a method for future sampling with the SuMo ROV for species and abundance (live cover) as well as animals associated with sponges in the sites of collection.
- Fragments of sponges from different morphological regions were either submitted to a bulk DNA extraction using standard techniques, or were separated into size fragments which were treated as separate samples for DNA extraction. The samples are currently being prepared for targeted 16S rRNA sequence analysis of the microbial metagenome. Bioinformatics pipelines for analyzing the resulting data have been developed and tested with similar microbial sequence data from carnivorous sponges from the Gulf of Maine.
- We will extract DNA and do metabarcodes of associated water samles. We plan to target archeae, bacteria and microbial eukaryotes.
- HD videos are presently being analysed by many laboratories in Canada as these analyses are time consuming.
- Samples from the 2015 expedition are analyzed in several laboratories across Canada and these analyses are underway.

6. Other activities

- PhD student Joost Verhoeven attended the Analysis of Metagenomic Data workshop in Halifax, NS (June 24-26, 2015), to learn bioinformatic techniques for the analysis of complex microbial communities (e.g. sponge microbiomes and sediment microbial communities).
- Participation to the Fall Safety Training (B. de Moura Neves, MUN, R. Steinhart, MUN).
- Participation to the Schools on Board program (2015) onboard the *Amundsen* (P. Archambault, C. Grant, R. Steinhart).

- Participation to a workshop on Adaptation Actions for a Changing Arctic Baffin Bay & Davis Strait Regional Assessment, Aarhus University, Danemark, June 9-11, 2015 (P. Archambault).
- Participation to the Expert Network State of the Arctic Marine Biodiversity Report (SAMBR) Writing Workshop of the CircumpolarBiodiversity Monitoring program (CBMP), CAFF Secretariat, University of Akureyri, Iceland, April 14-16 (C. Lovejoy, P. Archambault).
- Extensive networking with ArcticNet Frobisher Bay project, including one ROV dive shared with that project.
- Extensive networking with ArcticNet project Mapping of Arctic Canada's Seafloor. The imagery collected is very valuable to geologists and helps them to ground-truth the type of information collected with the acoustics mapping technology.
- Networking with Experimental Fisheries project at MUN Marine Institute, aboard Arctic Fisheries Alliance ship Kiviuq 1. We have been providing this group with ID guides and collection materials for corals, sponges, and other megafauna, which are recovered as bycatch in benthic longline fisheries. Documentation of very abundant sea pen fields in Jones Sound (2014), abundant sea pens and diverse sponges near Arctic Bay, Resolute, and Qikiqtarjuaq (2015).
- Networking with European researchers studying cold-water carbonate sediment producers in the Eurasian Arctic via COCARDE network (Cold-water carbonates in Shallow and Deep Time).
- Networking with the National Science Foundation project Polar Ice (leader Corey Garza, California State University, Monterey California). This project is for enhancing the capacity of polar scientists for communicating and engaging with diverse audiences. We are exploring presently how the HD video and pictures collected in HiBio could be used as virtual research opportunities for educators and students.

RESULTS

A total of five locations in Baffin Bay were chosen to be surveyed using the SuMo ROV during the *Amundsen* 2015 expedition: Navy Board Inlet, Pond Inlet, Scott Inlet, Cape Dyer, and Frobisher Bay (Figure 1). The dive at the Pond Inlet site was cancelled due to a combination of issues with the ROV and scheduling. As a result, a site near Qikiqtarjuaq (near station 177) was later added to the plan.

Dive 43: Navy Board Inlet (73.7149963 N, -81.1238022 W) October 15th 2015

At this site, the planned transect length was 2 km, but only ~450 m were surveyed due to electrical problems with the ROV. The surveyed line depth ranged between 434-453 m. Bottom temperature (452.8 m) at this site was -0.7 °C, and salinity was 33.63 PSU.

Echinoderms were the most commonly observed organisms, with brittle stars being the most abundant taxa observed during the dive. Other commonly observed echinoderms include the basket star *Gorgonocephalus* sp., the sea urchin *Strongylocentrotus* sp., sea cucumbers, the feather star *Poliometra* sp., the sea star *Crossaster papposus* and others. Sea anemones and ceriantharians were also frequently observed. Shrimps were also very conspicuous at this site.

Soft corals (Family Nephtheidae) were also observed, but not very frequently. Whelks and the jelly fish *Ptychogastria polaris* were also seen near the bottom during the dive. The carnivorous sponge *Cladorhiza* sp. was observed only once during this dive, but additional sponges were also seen, such as *Mycale* sp. and other undetermined species. Fish such as sculpins, Cottidae fish, and a sea tadpole *Careproctus reinhardi* were also observed.

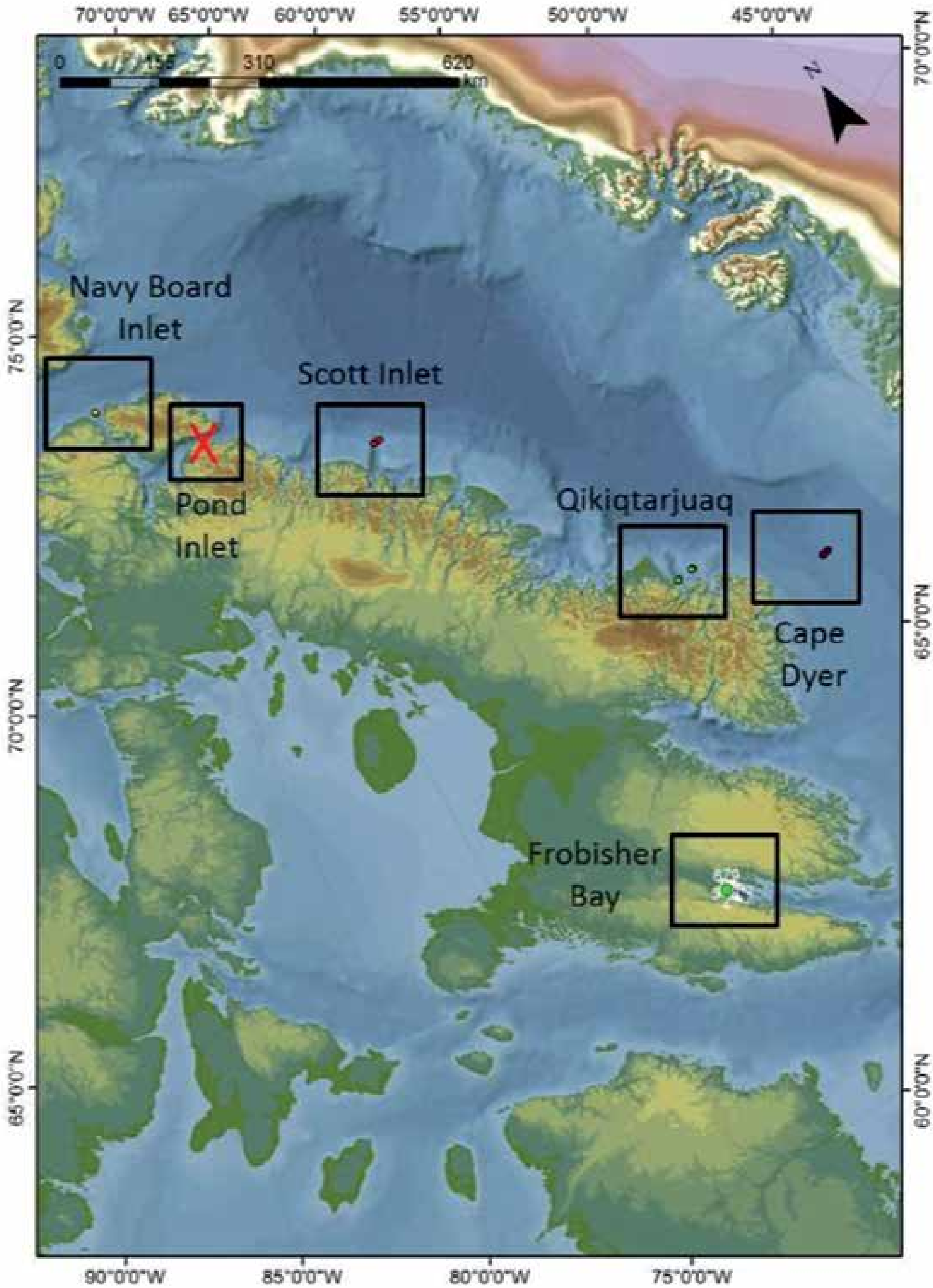

Figure 1. ROV dive locations for the 2015 CCGS Amundsen expedition. The Pond Inlet ROV dive was cancelled and replaced with the Qikiqtarjuaq dive.

In terms of bottom type, the surveyed site was mainly rocky. At certain areas the bottom was dominated by gravel, while in others it was dominated by cobbles and pebbles. Bedrock outcrops were also surveyed during this dive, being covered with polychaete tubes, sea urchins, and sponges.

Dive 44-45: Scott Inlet (71.5162964 N, -70.2777023 W) October 17th 2015

At this site, there was no pre-established transect to be followed, as the objective was the sampling of carnivorous sponges. The surveyed area was ~3428 m^2, ranging depths between 520-533 m. Bottom temperature (595 m) near the dive site was ~1.3 °C, and salinity was ~34.4 PSU.

The new sampling elevator was deployed at the evening of October 16th at a site where carnivorous sponges had been observed during the 2014 *Amundsen* expedition (elevator location: 71˚31.0031'N, 70˚16.6786'W; depth of 533 m). Total deployment time was 3 hours. On October 17th, we used the ROV and the sample elevator to successfully collect three carnivorous sponges from Scott Inlet during dives 44 and 45. During dive 44, one sample of *Chondrocladia* sp. was collected and placed in a sample box on the elevator. Due to technical issues with the ROV, dive 44 was aborted and a second dive (45) was undertaken a few hours later after ROV problems were resolved. During dive 45, a specimen of *Cladorhiza* sp. and a second specimen of *Chondrocladia* sp. were collected. Other organisms observed during dives 44 and 45 include sea anemones, the sea pen *Umbellula encrinus*, brittle stars, and additional sponges including vase sponges, whelks, as well as abundant copepods (and marine snow) in the water column (Figure 2). The bottom consisted of sand, mud, and abundant cobble. The elevator was successfully retrieved, and recovery time was 1 hour.

Dive 46: Qikiqtarjuaq (67.4741974 N, -63.6929016 W) October 20th 2015

An ROV dive near Qikiqtarjuaq (~4 km from station 177) was added to the plan, as a replacement to the dive that could not take place in Pond Inlet. A multibeam survey was conducted in the area before the dive, and the specific site was chosen based on high slope features. The original dive transect was planned to follow a line 1.5 km in length, but only 954 m could be completed due to time limitations. The transect path crossed depths ranging 620-680 m. Bottom temperature (370 m) was 0.8 °C (station 177), and salinity was ~34 PSU.

The dive transitioned from a flat slope area with muddy substrate (680 m), into a gentle slope with scattered boulders, concluding with rocky outcrops (620 m).

The Venus flytrap sea anemones (*Actinoscyphia* sp.) were the dominant organisms in the first part of the dive, forming dense fields (e.g. 2.8 individuals/ m^2) in the soft mud substrate. Other notable species included giant *Umbellula* sp. sea pens, with one individual reaching ~ 230 cm height, 75 cm width and having 56 polyps. Other organisms observed in the muddy substrate included: ascidians (*Ciona intestinalis*), ophiuroids (brittle stars, the basket star - *Gorgonocephalus* sp.), at least two species of decapods (shrimps), cnidarians (tube-dwelling sea anemones and solitary stalked hydrozoans - *Corymorpha* sp.), fish (skate sp., eelpout-*Lycodes* sp., Arctic alligator fish), whelk sp., sponges, and an unidentified cluster of small white tubes.

Towards the latter portion of the transect, larger boulders and rock outcrops were observed colonized by sponges (*Polymastia* spp., fan sponges), sea anemones, nephtheid soft corals, bryozoans, and crinoids. The community structure of the surrounding muds also transitioned with fewer Venus flytrap sea anemones but with stalked hydroids and more sponge observations such as *Chondrocladia* sp., *Cladoriza* sp., and stipitate/stalked sponges). The dive transect

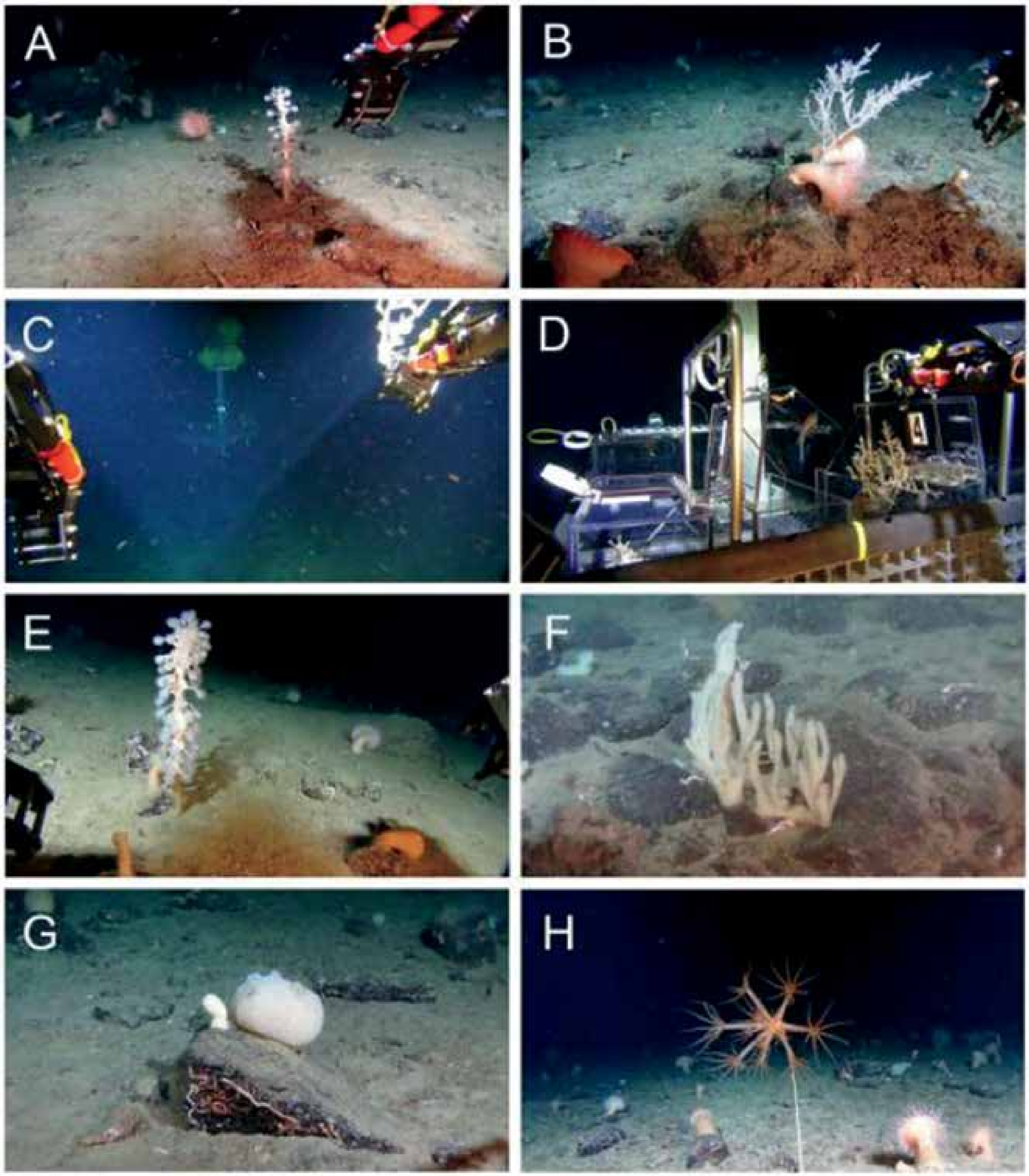

Figure 2. Organisms and bottom types observed during the ROV dive at Scott Inlet. A) Sampling of Chondrocladia sp., B) sampling of Cladorhiza sp., C) Cladorhiza sp. sample being brought to the elevator, D) Cladorhiza sp. being put in the box, E) Chondrocladia sp., F) fan sponge, G) Polymastia sp., H) Umbellula encrinus.

concluded at the base of a steep outcrop dominated by crinoids at 614 m.

Dive 47: Cape Dyer (66.4132996 N, -59.2184982 W) October 23th 2015

This site was chosen based on records of sponge bycatch and areas identified as having high sponge concentrations (Kenchington et al., 2010), with the dive transect crossing a trawl path from a 2006 DFO survey set. A multibeam survey was conducted over the site but in two parts; the majority completed before the dive and the remainder after the dive.

Sponges were the dominant organism found on both substrate types, and were composed of species from two classes: Demospongiae (*Geodia* spp., *Stryphnus-Aplysilla* spp., *Craniella* sp., *Polymastia* spp.) and Hexactinellida (*Asconoma* sp.). In many cases sponge species could not be determined due to thick layers of epifauna encrusting individuals. No samples were collected due to mechanical failure of the ROV arms.

Corals were also abundant at this site, with soft corals (nephtheid corals) observed on hard substrates, and the sea pen *Umbellula encrinus* in soft muds. Other notable groups observed during transect included: ascidians, echinoderms, arthropods (pycnogonids), decapods (shrimps), other cnidarians (sea anemones and solitary stalked hydrozoans - *Corymorpha* cf. *glacialis*), cephalopods (octopus and squid), and numerous fish species (Greenland halibut - *Reinhardtius hippoglossoides*, eelpout (*Lycodes* sp.), rockling - *Gaidropsarus* sp., sea tadpole – *Careproctus reinhardti*, and grenadier – Family Macrouidae).

Assessment of the impact of the single trawl from 2006 DFO Cosmos Trawl survey could not be confirmed in the preliminary results. However, upon review of processed multibeam data, linear features were observed and may indicate the site was exposed to more anthropogenic disturbances (e.g. bottom contact fishing gear) than originally thought, and would explain the relatively small size of many individual sponges (e.g. *Chondrocladia*) and overall low sponge biomass.

Dive 48: Frobisher Bay (63.6385994 N, -68.6306992 W) October 25th 2015

The dive started at 139 m depth in a soft bottom area outside of the landslide, where ascidians (*Ciona intestinalis*) were very abundant, forming fields. Echinoderms and isopods were frequently seen, including isopods with juveniles clustered on the front appendages of the adults. Large concentrations of kelp were observed, although it is undetermined whether the kelp is resident to the site or from shallower depths.

Brittle stars and feather stars were the dominant organisms in the landslide area, along with sponges (Desmospongia), while ascidians were much less abundant. In the landslide area crinoids were more abundant where slope was higher. The sea star *Solaster* cf. e*ndeca* was also observed in this part of the dive. The landslide ridges observed in the bathymetry could be identified during the transect as changes in the slope. Sporadic boulders encrusted with soft corals (few), sponges, crinoids and tube polychaetes. Fish (eel pout, sea tadpoles, and sculpins) were also observed. Juvenile scallops were also abundant in this part of the transect, with densities of at least 24 individuals/m^2. Picnogonids were also conspicuous in the landslide area.

After surveying the landslide area, we went back to the beginning of the dive in order to sample ascidians, and to give continuity to the transect in a high slope area. One globular sponge, one ascidian, and one arborescent sponge were successfully sampled using the ROV arms. Because the samples were kept in the ROV arm, only fragments of the arborescent sponge could be retrieved. The globular sponge had a peculiar garlic smell.

In the second part of the transect we surveyed the transition zone between a flat bottom environment and a rocky outcrop. A high concentration of ascidians and sponge gardens (dominated by arborescent sponges) were observed in this part of the dive, as well as crustaceans (isopods), sea cucumbers (probably *Psolus fabrici*), crinoids, ophiuroids, sea stars, sea anemones, and tube polychaetes. Fish were also seen throughout the dive, including a juvenile flatfish, alligator fish, and sea tadpoles.

DISCUSSION

We sampled three *Cladorhiza* and two *Chondrocladia* from Scott Inlet and Qikiqtarjuaq, and observed other individuals at Navy Board, Cape Dyer and Frobisher Bay, suggesting that these carnivorous sponges may be broadly distributed at shelf depths in Baffin Bay. Genomic analyses of their microbiome are currently under way.

CONCLUSION

These preliminary results indicate that the dives were successful, based on objectives specified in our original dive plan:

1. Invertebrates and fish diversity

- The diversity of sponges, corals, other invertebrates and fish was documented at all surveyed sites. These observations indicate high sponge concentrations and species richness in Cape Dyer and Frobisher Bay. Although biomass in Cape Dyer appears to be much lower than expected, dense sponge gardens were identified in the Frobisher Bay area (Figure 1). Future

ROV investigation in Frobisher Bay is highly recommended in order to better assess the ecological significance of this area.

- The presence of anemone fields and giant colonies of the sea pen *Umbellula* in the Qikiqtarjuaq area highlight the ecological importance of this site, where further ROV investigation is also recommended. We requested additional dives in this area for 2016, which we will also performed new incubation to understand the ecosystem functioning of this areas.
- Observations show corals co-occur with sponges as well as other benthic animals (e.g. fish, octopus, shrimp, hydroids, brittle stars, sea anemones, and bryozoans).

2. Steep/deep versus gravelly bottom sites

- The ROV survey at Navy Board (Figure 1) showed pebbles, boulders and bedrock dominated the substrate. As a result, this site would be unsuitable for traditional sampling methods such as box coring and trawling, and highlights the importance of ROV technology.
- An array of bottom types were observed in all five sites, from muddy bottoms to bedrock outcrops. The benthic fauna associated to the different bottom types was also distinct and dominated by different organisms, indicating the need to sample both types of habitats (e.g. soft and hard bottoms) to fully understand the biodiversity.

3. Size-frequency distribution of Umbellula encrinus

- Colonies of *U. encrinus* were observed in three of the five dive sites (Scott Inlet, Qikiqtarjuaq, and Cape Dyer). Based on our current knowledge on this species, substrates in Navy Board were inhospitable, and Frobisher Bay was too shallow. Size frequency distribution will be determined by analyzing the 19 h HD videos, with the assistance of the red lasers 10 cm apart that is used on the ROV.

4. New elevator system

- Collections using the new elevator system in Scott Inlet were successful, with several carnivorous sponges being obtained. Although the elevator could not be deployed at all three planned sites, samples were still collected utilizing SuMo's arms as an alternative.

5. Box cores

- Box cores planned in association with most of the dive sites were successfully collected (8 box cores sampled), and samples will be analyzed later for microbial and invertebrate fauna studies.

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Remote Sensing of Canada's New Arctic Frontier

Project Leader

Marcel Babin (Université Laval)

Collaborators

Éric Brossier (Université Laval)
Anne de Vernal (Université du Québec à Montréal)
Atsushi Matsuoka (Université Laval)
Xiaogang Xing (Université Laval)

HQP

Srikanth Ayyala-Somayajula, Doctoral Student (Université Laval)
Étude quantitative sur la variabilité du régime lumineux dans l'Océan Arctique: Implication pour les estimations de la production primaire dans le contexte du changement climatique
Walid Baccari, Doctoral Student (Université Laval)
Sophie Renaut, Doctoral Student (Université Laval)
Variability of Arctic ice edge blooms and the implication for the biological pump in a period of declining ice cover
Gauthier Verin, Doctoral Student (Université Laval)
Pierre-Luc Grondin, Masters Student (Université Laval)
Philippe-Israel Morin, Masters Student (Université Laval)
Marti Gali-Tapias, Post-Doctoral Fellow (Université Laval)
Clémence Goyens, Post-Doctoral Fellow (Université du Québec à Rimouski)
Thomas Lacour, Post-Doctoral Fellow (Université Laval)
Griet Neukermans, Post-Doctoral Fellow (Université Laval)
Guislain Bécu, Research Associate (Université Laval)
Maxime Benoît-Gagné, Research Associate (Université Laval)
Flavienne Bruyant, Research Associate (Université Laval)
Debbie Christiansen Stowe, Research Associate (Université Laval)
Emmanuel Devred, Research Associate (Université Laval)
Joannie Ferland, Research Associate (Université Laval)
Marie-Hélène Forget, Research Associate (Université Laval)
José Lagunas, Research Associate (Université Laval)
Catherine Lalande, Research Associate (Université Laval)
Jade Larivière, Research Associate (Université Laval)
Eric Rehm, Research Associate (Université Laval)
Julie Sansoulet, Research Associate (Université Laval)
Manon Bélanger, Undergraduate Student (Université Laval)
Constance Marty, Undergraduate Student (Université Laval)
Alexandre Petit, Undergraduate Student (Université Laval)

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

In the Arctic Ocean, as in most parts of the World Ocean, the phytoplankton spring bloom (PSB) provides a large fraction of the annual PP and, more importantly, nearly all of the new PP exportable through the food chain and toward the bottom sediments. The Arctic PSB often develops around the ice-edge (Perrette et al. 2011). This highly transient phenomenon lasts about 3 weeks at any given location in the seasonal ice zone (SIZ) and accounts for most of the annual PP in the Arctic Ocean (Wang and Overland 2012). The SIZ is currently increasing in size and may cover the entire Arctic Ocean as of the 2030s (ACIA 2005). Therefore, one may expect iceedge 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?

OBJECTIVES

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 Arctic Ocean. We hypothesize that PP at high latitudes will increase in the coming decades because of a northward expansion of the SIZ and an intensification of the phytoplankton spring bloom. We expect that changes in the phytoplankton phenology will have profound consequence on the entire ecosystem and food chain. The short-term objective (next five years) is to understand the dynamics of the Arctic PSB and, more specifically, how it is controlled by physical and chemical properties of the upper ocean and by phytoplankton species succession during the bloom.

INTRODUCTION

In the ocean, as in terrestrial environments, the food chain mostly relies upon the input of energy and organic matter at the level of so-called primary producers that achieve photosynthesis. Any significant change in PP will therefore have an impact on the entire food chain, from zooplankton to birds and mammals. Phytoplankton is responsible for most of marine PP. Its growth largely depends on available inorganic nutrients and light, and on temperature. In the Arctic, the place on Earth where climate change causes the deepest and fastest changes in terrestrial and marine environments (Ardyna et al. 2011), how will marine PP respond and what will be the impact on the whole marine ecosystem? The Arctic Ocean is characterized by a high biogeographic complexity and the existence of distinct PP regimes (Ardyna et al 2013, Perrette et al. 2011, Tremblay and Gagnon 2009). Pan-Arctic PP distribution reflects the combined role of vertical stratification and nutrient availability (Perrette et al. 2011, Tremblay and Gagnon 2009, Carmack et al. 2006). Primary production in the Arctic is highly influenced by water masses and the presence of sea ice, which limits the penetration of sunlight and air-sea interactions. The September extent of the Arctic Ocean icepack has decreased by nearly 40% over the last 3 decades. The resulting increase in the penetration of sunlight in the water column may boost PP of phytoplankton and, thereby increase the overall biological productivity in the Arctic Ocean.

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

In the different Arctic and sub-Arctic seas, this major pulse in PP represents between 40 and 65% of the total annual PP (Perrette et al. 2011, Lavoie et al. 2009, Tremblay and Gagnon 2009, Klein et al. 2002). In northernmost regions where the ice cover melts late, the PSB might account for an even greater proportion of the annual PP, as the short insolation period allows for only one pulse of photosynthetic production (Wang and Overland, 2012, Lavoie et al. 2009).

ACTIVITIES

Methodology - To verify our main hypothesis and determine the impact of the marine ecosystem, we need to 1) understand the key physical, chemical and biological processes that govern the 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.

Understanding the key physical, chemical and biological processes that govern the PSB

To develop a mechanistic understanding of the key physical, chemical and biological processes that govern the PSB, two PSB events will be monitored in Baffin Bay from its onset under melting sea ice in May to its conclusion within the SIZ in July. We will document i) the variations in the spatial distribution of physical properties and biogeochemical stocks during the PSB around the ice-edge, ii) the composition of the phytoplankton community and other relevant micro-organisms, iii) the physical processes that control the PSB, and iv) the phytoplankton physiological processes involved in bloom dynamics. The 2015 field campaign, between mid-April and mid-July, was designed to capture all phases (initiation, peak, decline) of the PSB. Operations were conducted from an ice-camp situated near the community of Qikiqtarjuaq, Nunavut. The 2016 campaign will be comprised a three month ice camp (May-July) and a 6-week oceanographic mission (early June-mid July) aboard the research icebreaker CCGS *Amundsen*. While the ice camp operations will remain at the same location relative to the ice-pack for entire period each year, measurements from the icebreaker will be made at stations along a quasi-zonal transect at around 69°N that will be traversed several times. The physical oceanography measurement component will focus on measuring the spatio-temporal variability of heat, salt, freshwater and momentum fluxes. Special efforts will be made to produce synthesized measurements that will be directly useful to the modelling effort for testing and calibrating various poorly known parameters (e.g. vertical diffusivity) used in physical and ecosystem models. Ship-base sampling in open-water will include a series of conventional Rosette-CTD profiles collected at all stations. Turbulence profiles will also be collected with vertical microstructures profilers (SCAMP, MVP). The distribution of major nutrients (all forms of nitrogen, phosphates and silicates), and particulate and dissolved organic carbon will be determined.

Identifying the key phytoplankton species involved in the PSB and model their growth under various environmental conditions

The planktonic community will be characterized over multiple levels since, in addition to diatom species, which will change over the course of the bloom, other co-occurring species will vary as well. This will be in particular the case of pico- and nano-phytoplankton, which form the background of the photosynthetic community (Matsuoka et al. 2013). Major phytoplankton groups will be determined from HPLC pigment analyses, larger cells will be identified and enumerated using inverted microscopy, and smaller cells will be counted by flow cytometry. In addition, we will isolate the most abundant small phytoplankton species by flow cytometry sorting (small cells) and under the microscope using pipettes (large cells). DNA and RNA will be collected to determine overall plankton diversity using high throughput SS rRNA gene surveys. Fast changes in the phytoplankton community during the PSB will be monitored using a single-cell counter/imager (FlowCytobot,) owned by Takuvik. We will extensively document the variability in photosynthetic parameters, and determine primary, new and regenerated production. Autonomous platforms (gliders and bio-argo floats) will be used to automatically sample the physical and the biogeochemical parameters of interest in the PSB, at different regional scales

Determining the transfer of carbon produced by the PSB through the food web and towards the bottom sediments

As part of this project, we will also establish a solid connection with the coastal communities that populate western Baffin Island with the aim of documenting the links between climate change, fluctuations in vernal productivity, and the variability in marine resource density and diversity. This will take the form of a series of interviews and bilateral discussion between elders, middle-aged and young Inuit, as well as my group. Inuit knowledge of the marine environment will be gathered with Elders, hunters and identified local experts using a semi-directive interview process and map biographies. Data gathered will be analyzed and synthesized using a process of thematic content analysis. As well a Geographic Information System (GIS) database will be created and spatial distribution of key ecological phenomena will be explored. We aim specifically at targeting the local communities of Clyde River, Pond Inlet and Qikiqtarjuaq. Those three locations are all situated within coastal embayments that constitute the termination points of the SIZ. They provide the perfect setting to get insights on the timing of ice melt and inter-annual variability in fish and marine mammal abundance as the ecosystem matures over spring-summer. Within Green Edge, this traditional knowledge dataset will represent a fourth method (i.e. after remote sensing, sclerochronology, and sediment cores) of documenting the climate-driven trends and ongoing changes in productivity and carbon transfer in Arctic waters.

Documenting trends in the spatial and temporal variations of the PSB

Ocean color remote sensing is a valuable tool for monitoring phytoplankton in the often inaccessible Arctic Ocean, despite a number of difficulties inherent to this region, including extreme cloudiness during late summer and early fall. Using this technique, trends in annual PP since 1998 have been documented for the first time at pan-Arctic scale, and the contribution of the ice-edge spring bloom to annual PP was assessed. In the present project, we will use ocean color remote sensing to thoroughly study the Arctic PSB, the full phenology of phytoplankton biomass, as well as transient phytoplankton blooms triggered by forcing events such as shelf-break upwellings. We hypothesize that the recent expansion of the SIZ and the resulting increase in air-sea interactions are responsible for the observed increasing PP in some parts of the Arctic Ocean. We will first solve a number of problems we currently face with this technique. Ocean color remote sensing close to the ice-edge in open waters is difficult because of signal contamination due to the proximity of the ice-edge (adjacency effect) or the presence of sub-pixel ice floes. Also the optical properties of seawater close to the ice-edge are often peculiar. They affect the performance of ocean colour algorithms used to estimate phytoplankton concentration. Finally, it is obviously impossible to detect phytoplankton from space through the ice-pack, therefore making it difficult to monitor the fraction of the spring bloom that takes places under sea ice. So, to optimize our remote sensing approach to estimate PP in the Arctic Ocean, and especially that due to the spring bloom, we will conduct the following three activities: 1) We will document the inherent and apparent optical properties of seawater in the vicinity of the ice edge, and the variations in their spatial distribution during the phytoplankton spring bloom. These data will be used to optimize our ocean colour algorithms for estimating chlorophyll a, as well as our PP model; 2) We will develop a new correction approach for the contamination of the water-leaving radiance signal, resulting from the adjacency effect and for the presence of sub-pixel ice floes: and 3) We will develop an approach based on multi-source remote sensing data for estimating at best the incident irradiance at the top of the water column in ice-covered areas, that can support phytoplankton PP. Finally, all new tools developed in the frame of the first three activities will be used for: 4) Establishing times series of pan-Arctic PP over the period for which remotely sensed ocean colour data are available, including the CZCS era, studying the phytoplankton phenology at the pan-Arctic level (MSc-3), developing and using an algorithm based on ocean colour for estimation of DMS production, and developing a new fluorescence-based algorithm to quantify phytoplankton biomass more specifically for coastal applications. For all those activities, *in situ* data will be collected on inherent optical properties (absorption and scattering coefficients), and apparent optical properties (radiance and irradiance) to described the in-water and surface-upward structure of the light field for algorithm development and validation.

RESULTS

During the 2015 field season (mid-April- mid-July), we set up an ice camp 30 km off the community of Qikiqtarjuaq (67° 29.23N and 63° 38.00W) consisting of a Polarhaven tent and a wooden cabin built on a sledge. The camp was dismantled on June 24h, but we continued to visit the site until July 14. We conducted nearly 50 days of full-station sampling at the ice camp between mid-April and mid-July, transporting scientists and equipment by skidoo and Qamutik. Over this period twenty different categories of measurements were conducted. Forty-seven people participated in GreenEdge ice camp activities in 2015.

Snow and sea ice optical properties

We measured the vertical profile of spectrally-resolved radiative fluxes in the snow using a recently developed SOLEXS instrument as well as snow spectral albedo and seven vertical profiles of snow specific surface area (SSA) and density. In addition, we observed snow stratigraphy and grain shape. This first field season was devoted to adapting the technologies developed for the study of cold dry snow in continental areas to the study of wet snow on sea ice. We were also able to measure light transmission through sea ice and through the snow + sea ice system in order to quantify the impact of snow on irradiance at the top of the ocean. Complementary sea ice optical properties were measured by researchers from the University of Manitoba (Jens Ehn). These data will be essential to run and test our optical models of snow and sea ice.

Physical oceanography

Real-time continuous measurements of sea ice mass balance were collected by deploying an Ice-T buoy. This instrument provided real-time measurements of sea ice thickness and heat content evolution, as well providing as an estimate of the ocean-ice heat fluxes. The Ice-T buoy was further equipped with a fluorometer (for chlorophyll a concentration; chl-a), and dissolved oxygen and nitrate sensors to test concomitant biochemical measurements which are important for understanding the dynamics of phytoplankton blooms and sea ice algae. A meteorological station, 'BEAR', was deployed to obtain the data used for the calculation of surface energy budget. Continuous records of the fine-scale (~1 m vertical and ~60 s temporal resolution) vertical structure of water properties were obtained by deploying downward-looking acoustic Doppler current profilers (ADCPs). This dataset was complemented by hourly Conductivity-Temperature-Depth (CTD) profiles during a 12-hour experiment and by daily CTD profiles. Turbulent properties of the water column were also measured by deploying a vertical microstructure profiler (SCAMP). These measurements will vertical eddy mixing coefficients as well as heat, salt and nutrient turbulent fluxes throughout the water column to be calculated.

The Ice-T buoy worked nominally. An example of the collected data, the temperature field in the ice measured by a chain of 32 thermistors located along the main surface buoy, is shown in Figure 1 from late March to early June, displaying an ample diurnal cycle at the surface, sometimes exceeding 20°C, quickly damped in the sea ice, where temperature gradually becomes nearly constant (freezing point) near the bottom. The buoy recovery campaign was substantially shortened due to adverse meteorological conditions that prevented northbound flights for several days. Therefore only three profiles with a self-contained autonomous microprofiler (SCAMP), down to 95 m, could be performed, while a series of 24 profiles during a full tidal cycle was initially planned. Such direct measurements are relevant to tune finescale parameterizations based on CTD and velocity profiles to be used to estimate vertical diffusivity in the upper ocean during the entire duration of the experiment. The SCAMP was left on site for the tidal cycle sampling operations to be subsequently performed by Canadian colleagues. Unfortunately, these operations could not be completed due to instrument failure (water leakage) after a few profiles.

More than 50 CTD profiles were performed from mid-March to mid-July (Figure 2). A fluorometer completed the suite of sensors to provide a proxy for chlorophyll concentration. Even though the seawater was still covered with ice at sampling time, the temperature and salinity sensors demonstrated the progressive stratification of the water column as surface temperature is warming up. From mid-June, a freshening (reduction of ≈1 salinity unit) and a warming (increase of ≈ 1°C) of the surface water

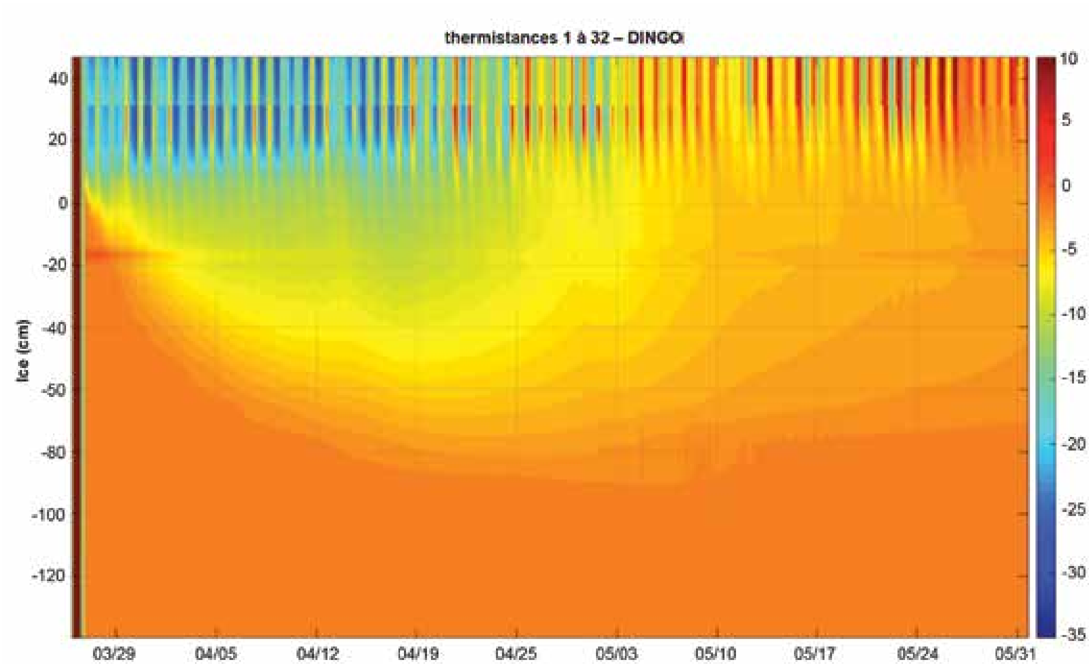

Figure 1. Evolution of the temperature field within the air/snow/sea-ice from March to June 2015 from the thermistor chain of the ice-T buoy (the slight warm temperature bias from the thermistor located at -20cm is an artifact). The color scale ranges from -30 to 10 °C.

are observable from the CTD profile from June 18th, as the ice start to melt. The fluorescence time series shows the discharge of ice algae in the water column in mid-June and their sinking, becoming a sub-surface maximum between 20-40 m, until the end of June. Then from the beginning of July, the fluorescence signal is increasing at the surface. On July 10th, the temperature sensor showed a signal of temperature peaking over 1°C associated with a drastic increase (x2) of the fluorescence signal, which reveals the onset of the phytoplankton bloom beneath the ice. This series of measurements will provide detailed information about the stratification and mixing of the water column associated with biological events.

Bio-optical characterisation and modelling of PSB

Inherent optical properties (IOP) profiles were measured using an IOP frame. The physical and optical sensors included: a FastCat 49 CTD (Seabrid Electronics), a AC-S hyperspectral absorption and attenuation meter (in the visible part of the spectrum; Wetlabs Inc.), a LISST particle size distribution sensor (32 sizes bins ranging from 1.25 microns to 250 microns; Sequoia Scientific Inc.); an ECO puck sensor (WETLabs Inc.) fitted with a Chl-a fluorescence probe, a CDOM fluorescence probe and a 700 nm backscattering probe and a ECO puck sensor (WETLabs Inc.) fitted with three backscattering probes at 720, 770 and 870 nm. Colored dissolved organic matter (CDOM) was measured from seawater and sea-ice samples using an ultrapath, following the methods described in (Riedel et al., 2008) and (Tassan and Ferrari, 2002).

Apparent optical properties were measured using the IcePro version of the C-OPS (Compact-Optical Profiling System, Biospherical Instruments Inc.) (Figure 7). Two irradiance sensors were mounted on the IcePro frame to measure the spectral upwelling ($E_u(z)$) and the spectral

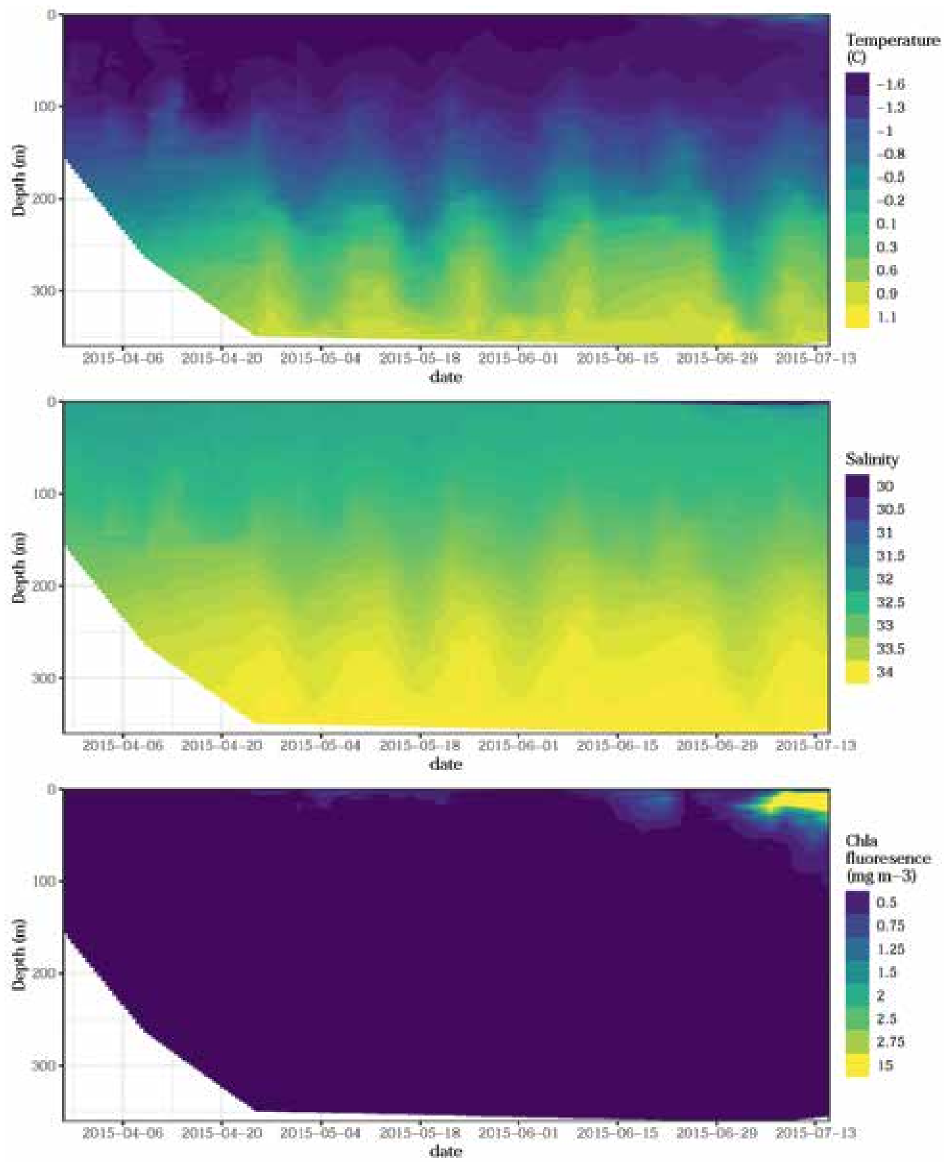

Figure 2. CTD profiles of temperature (upper panel), salinity (middle panel) and chlorophyll a fluorescence (bottom panel) deployed from a hole inside the Polarhaven tent from mid-March to mid-July 2015.

downwelling ($E_d(z)$) irradiance profiles at the same 19 wavebands (namely 380, 395, 412, 443, 465, 490, 510, 532, 555, 560, 589, 625, 665, 683, 694, 710, 765, 780 and 875 nm), from just underneath the ice down to 100m. An atmospheric reference sensor measured the downwelling irradiance at the bottom of the atmosphere. Next to the atmospheric unit, a GPS receiver allowed geo-localization of the measurements. These data, and complementary water sample analyses (see Succession of primary producers in ice-covered waters section), will be used to optimize our ocean colour algorithms for estimating chlorophyll *a* from remote sensing data and our PP models.

The ice algae discharge in the water column was observable (Figure 3) by an increase in CDOM signal from day 118 (April 28) to day 157 (June 6). This likely originated from ice algae (and phytoplankton) exudation.

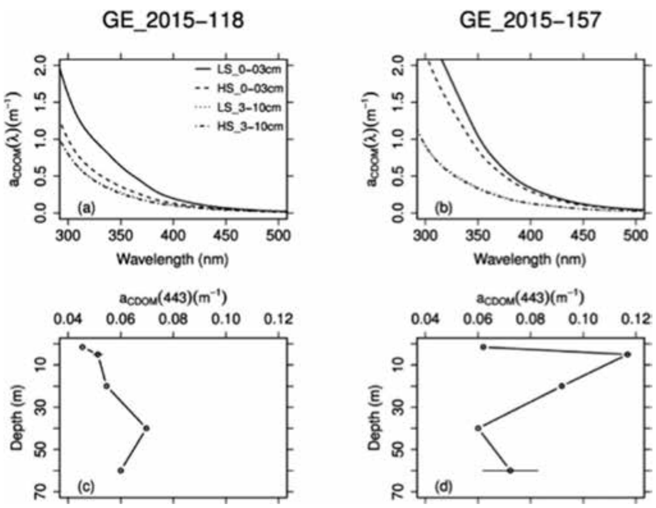

Figure 3. Panels on the left represent day 118 and panels on the right represent day 157. The upper panels show aCDOM spectra and the lower panels show aCDOM (443 nm) profile from surface to 60m in the water column.

In early May, light transmission peaked at 500nm and was ≈1% for snow depths of a few cm vs. ≈-0.1% for snow depths of 35+ cm (Figure 4a), resulting in respective subice Photosynthetically Active Radiation (PAR) of ≈ 10 µEin m^{-2} s^{-1} vs ≈ 1 µEin m^{-2} s^{-1} (Figure 5a). Strong differences in spectral shape were also observed due to light absorption by ice algae, which were abundant at the bottom of the ice with low snow coverage, but not under high snow coverage (Figures 4b,c). This supports the hypothesis that light is the limiting factor for sea-ice growth in early spring.

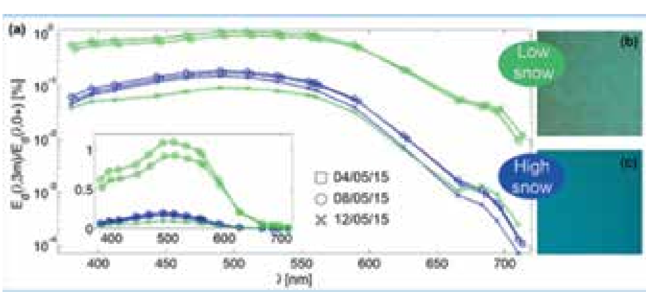

Figure 4. (a) Spectrum of light transmittance through sea ice and snow cover on three days in May 2015 under low and high snow cover. Inset shows the same data with linear y-scale. Shots of the underside of the sea ice taken ≈ 5 cm below the ice with a GoPro camera under low snow (b) and high snow (c) coverage.

Under high snow coverage, PAR was found to increase with depth reaching maximum values at ≈ 3-10 m (Figure 5a) due to the influence of adjacent areas of low snow cover. Deep irradiance maxima are a wavelength dependent phenomenon; they were absent at wavelengths where water absorption is high, >600nm (Figures 5b, 6b). These features resemble previous observations of irradiance profiles below bare ice with adjacent ponded areas.

Succession of primary producers and other biological stock variables in ice-covered waters

Sea ice and water column samples were collected at all 50 time-series stations and preserved for analysis in different laboratories. Core variables to be analysed include total inorganic carbon (TIC), nutrients (NO_3, NO_2, NH_4, PO_4, and $Si(OH)_4$), chlorophyll a (Figure 7), particulate organic carbon (POC) and nitrogen (PON), dissolved organic carbon (DOC), protist taxonomy, spectral light absorption of particulate matter, and concentrations of dimethylsulfide (DMS) and dimethylsulfoniopropionate (DMSP) (Kiene

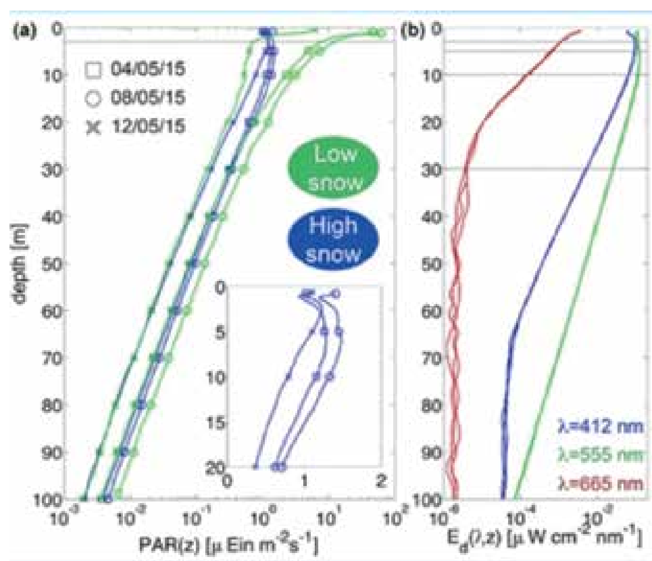

Figure 5. (a) Vertical profiles of PAR, on May 4, 8 and 12, 2015 under low and high snow coverage. Inset shows the top 2 meters of the water column with linear x-scale. (b) Vertical profiles of downwelling irradiance under high snow coverage on May 8, 2015 for 3 wavelengths, showing 3 replicates.

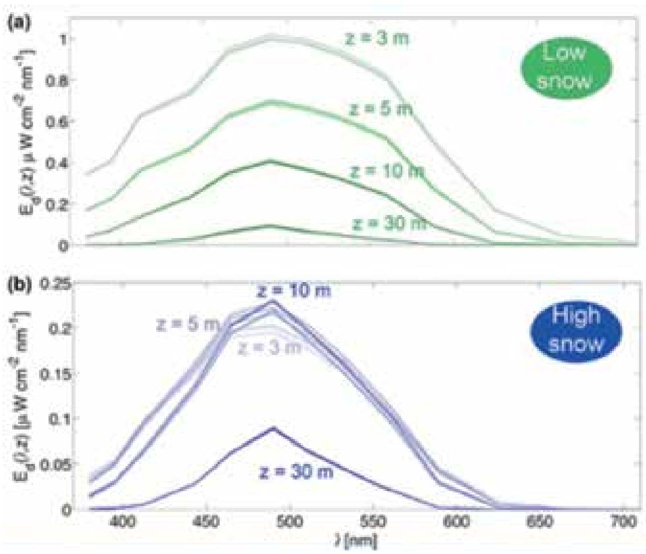

Figure 6. (a) Spectrum of downwelling irradiance at various depths on May 8, 2015 under low snow coverage, 3 replicates. (b) Spectrum of downwelling irradiance at various depths on May 8, 2015 under high snow coverage, showing 3 replicates.

and Slezak, 2006; Levasseur et al., 1994), pico- and nanoplankton as well as heterotrophic bacteria abundances, biomarkers and isotopic analyses (IP25, Fatty acids, sterols and alkenones) (Belt et al., 2007). Major phytoplankton groups will be determined from pigment analyses via high performance liquid chromatography (HPLC) (Zapata et al., 2000), larger cells will be identified and enumerated using inverted microscopy. Fast changes in the phytoplankton community during the PSB were monitored using a single-cell counter/imager (Image FlowCytobot; Figures 8,9). DNA and RNA were also collected to determine overall plankton diversity and in particular to identify heterotrophic groups using high throughput SS rRNA gene surveys (Comeau et al., 2011).

The chlorophyll a concentration measured by fluorimetry and the cell abundance and images from the IFCB provided near-real time indicators of the biological activities beneath the ice. We captured the ice algae bloom dominated by penate diatoms that were flushed from the ice around June 14. This was demonstrated by an increase number of cells and chlorophyll a concentration in Figures 7 and 8 and a

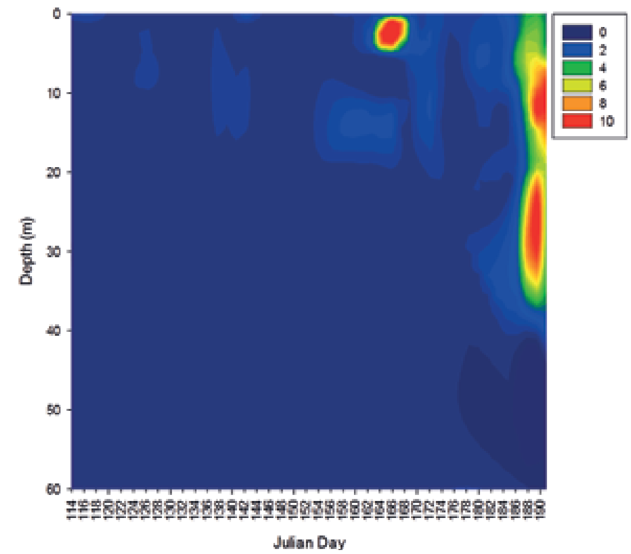

Figure 7. Chlorophyll a concentration from mid-March to mid-July in the seawater presented per depth of sampling.

clear decrease in abundance from ice counts (Figure 9). After this biological event, the images collected by the IFCB demonstrated a succession in species from penate diatoms to chain centric diatoms (data not shown) and a constant increase in image counts and chlorophyll a concentration. The onset of the PSB event remains to be related to physical and chemical changes in the marine environment. This PSB happened later then expected this year as the ice melt was delayed by approximately two weeks, as shown by satellites images of sea-ice concentration (AMSR-2 data) compared to the 1980-2014 climatology (Figure 10).

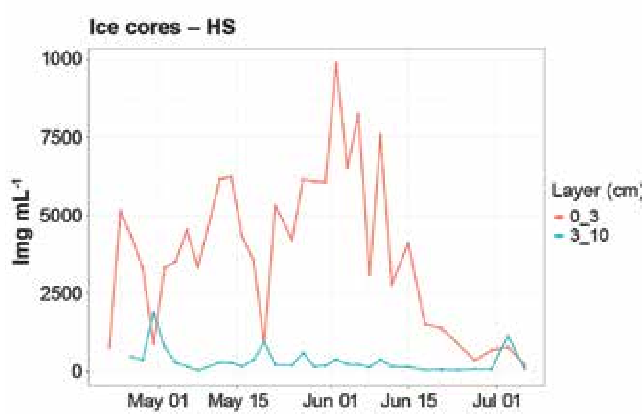

Figure 8. Average number of image abundance reflecting cell abundance per millilitre of seawater for each sampling depth and each sampling day, as measured from IFCB.

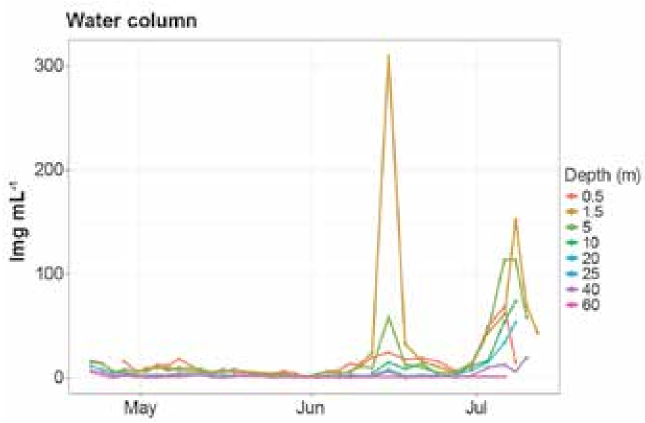

Figure 9. Average number of images reflecting cell abundance per millilitre in sea-ice covered by high snow condition for each sampling day as measured from IFCB.

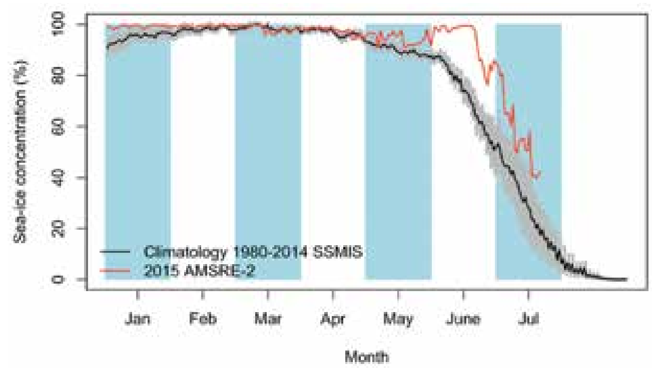

Figure 10. Time series of sea-ice concentration as observed from satellite images (AMSR-2 data) for 2015 (red line) and the climatology from 1980-2014 (black line).

Related carbon transfer through the food web and towards the bottom

Net tows (50 and 200 µm mesh size) were performed at the ice camp. Zooplankton samples collected will be analysed for mass, elemental (C:N) and isotopic composition ($\delta^{13}C/\delta^{15}C$) in order to detect shifts in their diet composition (Forest et al., 2011a). Additionally, deployments of short-term trap arrays (i.e. both bottom-anchored and ice-tethered) complemented the long-term trap sampling (shipbase) with the aim of following carbon export at a high temporal frequency and for collecting flocculated aggregates derived from the waning of the bloom. Zooplankton biomass data obtained through net tow sampling will be compared against those obtained with an Underwater Vision Profiler 5 (UVP5; Picheral et al., 2010) in order to provide an enhanced portray of pelagic grazer activities surrounding the bloom. As such, the UVP5 is an efficient instrument for the quantification of large-scale patterns in zooplankton biomass, as the upper size-range corresponds to the large calanoid copepods that dominate (~70-90%) mesozooplankton biomass in Arctic waters (Forest et al., 2012a) and serve as the main energy funnel from phytoplankton to fish (e.g. Darnis et al., 2008; Ringuette et al., 2002). Here, the combination of multiple techniques will have the advantage of documenting plankton thin layers as well as the whole end-to-end zooplankton population, including fragile gelatinous species. Anomalies in the shape of the size spectrum (1 µm – 1 cm) of plankton biomass will be used as indications of excess growth/mortality or gain/losses through consumption or vertical migration (Frangoulis et al., 2010; Zhou, 2006).

An increase in total particulate matter (TPM) fluxes, Chl a fluxes, fecal pellet carbon (FPC) fluxes, and fecal pellet width was observed at 25 m at the end of May (Figure 11). Whereas TPM fluxes and FPC fluxes also increased at 100 m during the same period, Chl *a* fluxes and fecal pellet width at that depth remained similar than in April and earlier in May (Figure 12). Chl a fluxes, FPC fluxes, and fecal pellet widths were higher at 100 m than at 25 m in April and most of May, but were similar at both depths from the end of May to the end of the deployment in June (Figures 11, 12). These results, along with the observation of larger copepods collected in the 25 m-trap at the end of May and in June only, indicate that the large copepods contributing to most of the zooplankton biomass and FPC fluxes migrated towards the surface at the end of May when primary production in the upper waters increased, as reflected by enhanced Chl a fluxes. Similarly, wide fecal pellets at 25 m and 100 m at the end of May and in June also support the migration of larger copepods from deeper waters towards the surface. However, while the composition of the export fluxes varied differently at 25 and 100 m, the magnitude of the TPM exported at both depths

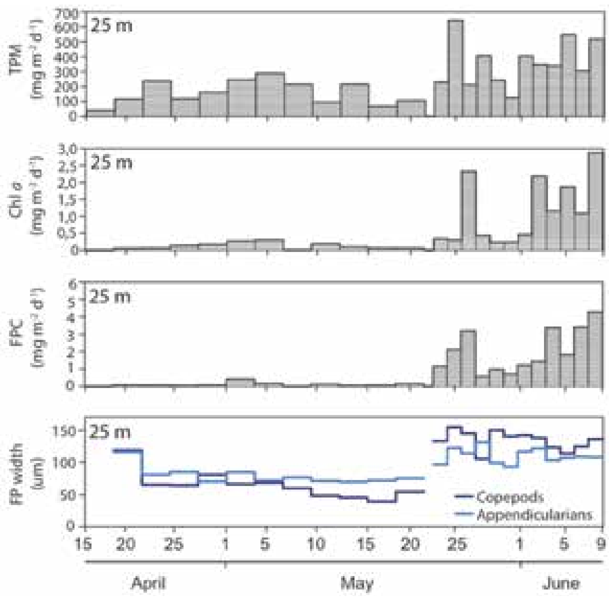

Figure 11. Under-ice export fluxes of TPM, Chl a, FPC, and fecal pellets width measured at 25 m from April 15 to June 9 2015.

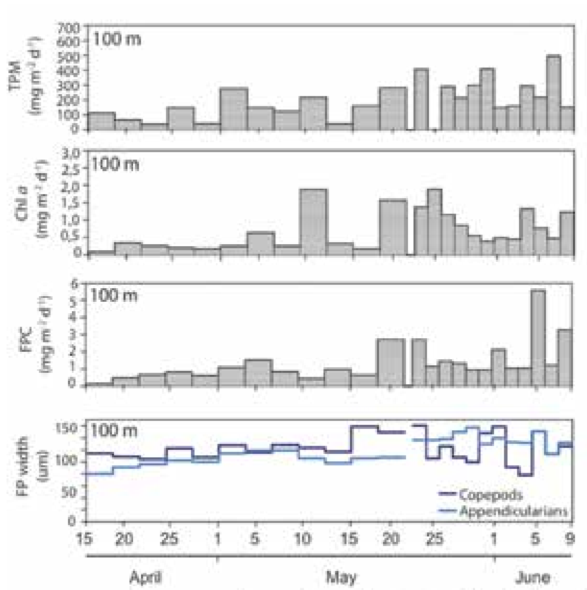

Figure 12. Under-ice export fluxes of TPM, Chl a, FPC, and fecal pellets width measured at 100m from April 15 to June 9 2015.

was similar from April to June. Overall, these results indicate a temporal change in the composition of the export fluxes even though there was > 1 m of ice and > 15 cm of snow above the sediment traps for the complete sampling period.

Post field season activities

Members of the GreenEdge consortium held a workshop in Paris, France November 4-6, 2015 to present the advancement of their sample and data analyses, create new collaborations and discuss the project timeline for next year field season. The implementation of the coupled bio-physical model using field measurements as also discussed at the workshop. GreenEdge data is being archived on the web (http://www.obs-vlfr.fr/proof/php/GREENEDGE/greenedge.php) with the collaboration of Catherine Schmechtig, manager of the LEFE CYBER database. This publically accessible site will facilitate the access to GreenEdge data by all consortium members.

Conclusion, Discussion, Acknowledgements and References sections are not provided in this project.

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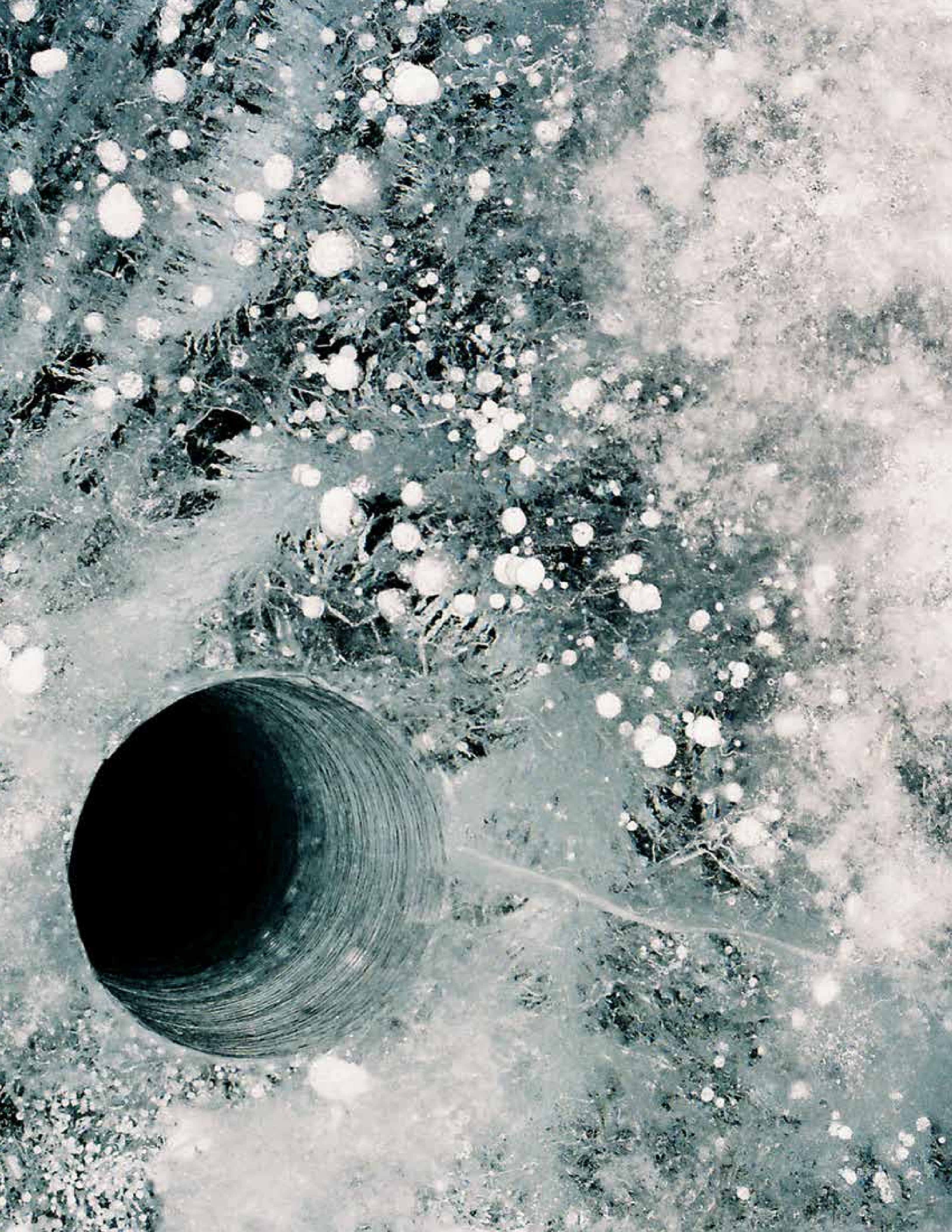

Sea Ice – Understanding and Modelling Ocean-Sea Ice-Atmosphere Biogeochemical Coupling in a Changing Climate

Project Leader

Dave Barber (University of Manitoba)

Network Investigators

Jens Ehn (University of Manitoba)
Steven Ferguson (University of Manitoba)
Michel Gosselin (Université du Québec à Rimouski)
Mats Granskog (University of Manitoba)
Christian Haas (York University)
Zou Zou Kuzyk (University of Manitoba)
Youyu Lu (Fisheries and Oceans Canada - Bedford Institute of Oceanography)
Tim N. Papakyriakou (University of Manitoba)
Soren Rysgaard (University of Manitoba)
Gary A. Stern (University of Manitoba)
Jean-Eric Tremblay (Université Laval)
Peter Wadhams (University of Cambridge)
Feiyue Wang (University of Manitoba)
John Yackel (University of Calgary)

Collaborators

Lucassie Arragutainaq (Hamlet of Sanikiluaq)
Igor Dmitrenko (University of Manitoba)
Torsten Geldsetzer (University of Calgary)
Vic Gillman (Fisheries Joint Management Committee (FJMC))
Joel Heath (Simon Fraser University)
Haakon Hop (Norwegian Polar Institute)
Jennifer Lukovich (University of Western Ontario)
Mike McKernan (Stantec)
Son Nghiem (NASA - National Aeronautics and Space Administration)
Masayo Ogi (University of Manitoba)
Desmond Power (C-CORE)
Andrey Prushutinski (Woods Hole Oceanographic Institute (WHOI))
Monika Pucko (University of Manitoba)
Kevin Sydor (Manitoba Hydro)

HQP

Nariman Firoozy, Doctoral Student (University of Manitoba)
Sea-ice inverse scattering
Shabnam Jafarikhasragh, Doctoral Student (Centre for Earth Observation Science (CEOS))
Satwant Kaur, Doctoral Student (University of Manitoba)
Jack Landy, Doctoral Student (University of Manitoba)
Sea ice surface morphology
Rong Li, Doctoral Student (Centre for Earth Observation Science (CEOS))
Vlad Petrusevich, Doctoral Student (Centre for Earth Observation Science (CEOS))
Geophysical and Biological Tracers in Water Dynamics of Arctic Shelf and Estuaries

Rosemary Eastwood, Masters Student (Centre for Earth Observation Science (CEOS))
Claire Hornby, Masters Student (University of Manitoba)
Krista Kenyon, Masters Student (Centre for Earth Observation Science (CEOS))
Thomas Neusitzer, Masters Student (Centre for Earth Observation Science (CEOS))
Oksana Schimnowski, Masters Student (University of Manitoba)
Megan Sheilds, Masters Student (University of Manitoba)
Chris Stammers, Masters Student (Centre for Earth Observation Science (CEOS))
Surface heat loss associated with open water environments during the fall and winter
Heather Stark, Masters Student (University of Manitoba)
North Water Polynya sea ice processes
Tyler Tiede, Masters Student (Centre for Earth Observation Science (CEOS))
Yu-Bin Hu, Post-Doctoral Fellow (University of Manitoba)
David Babb, Research Associate (University of Manitoba)
Lucette Barber, Research Associate (University of Manitoba)
Lauren Candlish, Research Associate (University of Manitoba)
Sergei Kirillov, Research Associate (Arctic and Antarctic Research Institute)
Greg McCullough, Research Associate (University of Manitoba)
Rick Raddatz, Research Associate (University of Manitoba)
Nathalie Theriault, Research Associate (Centre for Earth Observation Science (CEOS))
Kerri Warner, Research Associate (Centre for Earth Observation Science (CEOS))

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

1. During the past fiscal year (April 2015 – March 2016) we have produced 45 peer-reviewed publications, and we have also presented at over a dozen different international conferences.
2. We have participate in five major field programs: SERF winter 2016, CCGS *Amundsen* ArcticNet Cruise summer 2015, ASP St Nord field Campaign spring summer 2015, GreenEdge Field Camp Spring 2015 and the Belcher Islands Field Campaign Winter 2016.
3. Landy et al. (2015b) developed an empirical model that can predict melt pond fraction. Using this model they were able to reveal the possibility for an inter-annual feedback loop between winter sea ice roughness and summer surface melt.
4. Stark et al. (2016) developed an index classification algorithm to generate a universal method that would classify the dynamics of multiple polynya types using a passive microwave dataset. The algorithm results demonstrate a shift in the timing of both the formation and dissolution of the North Water Polynya, with both occurring earlier in the year. On average, NOW remained open for 81 days; however, there is considerable variation in this as it was open for 48 days in 1987 and 144 days in 2006.
5. The Hudson Bay Complex (Hudson Bay, James Bay, Hudson Strait, and Foxe Basin) is a highly dynamic environment undergoing rapid change. The Complex currently experiences surface air temperatures that range from seasonal averages of -10 to -30˚C in the winter and 0 to 12˚C in the summer. These temperatures are warming rapidly in all areas of the Hudson Bay Complex, particularly in the fall. This warming is expected to continue into the future, with projections calling for an increase of nearly 1˚C per decade in the annual average temperature of the Complex between 2012 and 2061 (Andrews et al. (2015).
6. Luckovich et al. (2015) investigated spatio-temporal characteristics of sea ice drift and state through development of temporal scaling maps to quantify distinct dynamical regimes using partial statistics. Results from this investigation highlight regional differences in absolute dispersion statistics, scaling laws and temporal scaling maps for the surrounding Beaufort region and the interior of the Beaufort Gyre, and within the PIZ and SIZ ice regimes.

OBJECTIVES

1. Macro-scale – *Examine the role of regional to hemispheric scale oceanic and atmospheric forcing (in both space and time) of sea ice dynamic and thermodynamic processes.*

2. Micro-scale – *Investigate the exchange processes at the micro- to local-scale of mass and energy across the ocean-sea ice-atmosphere (OSA) interface with a particular emphasis on high frequency atmospheric and oceanic events and examine the regional variability.*

3. Community-Based Monitoring (CBM) – *Continue with work linking Western science and Inuit knowledge (IK) through community-based monitoring programs.*

4. Technology – *Develop quantitative tools to estimate the geophysical and thermodynamic state of the snow/sea ice 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.*

INTRODUCTION

There have been dramatic changes to the sea ice regime in all sectors of the Arctic. Recently, Babb et al. (2015) 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. (2014) 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 multi-year ice (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.

Over this final cycle of ArcticNet we will continue to develop our understanding of the interactions between the atmosphere, ocean and sea ice in terms of the dynamic and thermodynamic processes. We will model future changes in sea ice based on this knowledge and examine the consequences of this change on various aspects of ecological and geochemical cycles operating across the ocean-sea ice-atmosphere (OSA) interface. To accomplish this we are examining these interacting systems at a range of space and time scales. Our field campaigns have focused on a several different regions of the Arctic: a) the Beaufort Sea, Canada Basin and Amundsen Gulf, b) Baffin Bay and Kane Basin, c) Greenland, d) Hudson Bay. As part of our objectives we look at the regional differences for the processes that are occurring in the Arctic through these field campaigns as well as try to replicate the processes with our mesocosm studies at the Sea ice Environmental Research Facility (SERF) in Winnipeg.

ACTIVITIES

Our field activities below are listed by field campaign, subdivided into the relevant sub-projects.

Sea-ice Environmental Research Facility (SERF) -Winnipeg- Winter 2016

Measurement of sea ice physical properties using Multilevel Transmission Lines and Ground Penetrating Radar (GPR) – Collaborative project with David Barber and Elena Pettinelli at Roma Tre University, Italy

Precise estimation of sea ice thickness and ice/brine ratio are difficult to be made in situ. Electromagnetic methods are the most suitable techniques to evaluate such parameters as they can be inferred starting from the dielectric properties of the ice. In this experiment we use time and frequency domain techniques to monitor, in real time, sea ice formation, growth and evolution in time. We will estimate the vertical distribution of the dielectric parameters during ice growth using a multilevel probe made of a series of horizontal transmission lines (4 cm apart) connected to a Vector Network Analyzer. From such parameters, using appropriate mixing models, the vertical distribution of brines and the ice salinity will be computed. These results will be compared with the data collected using vertical probes (of different length) and Ground Penetrating Radar (GPR) equipped with 1000 and 500 MHz antennas. In particular, GPR will be extensively employed to measure ice thickness and study the effect of the brine distribution on the estimation of the ice depth.

Carbonate system & phosphate evolution during sea ice growth and decay – Collaborative project with Yubin Hu, Fei Wang, Soren Rysgaard and David Barber

Dissolved inorganic carbon (DIC) in sea ice is an important parameter to describe the ocean-sea ice-atmosphere CO_2 flux. For a long time, sea ice was considered as a lid over seawater, preventing CO_2 exchange between the atmosphere and ocean (Tison et al. 2002). Recent observations suggest that sea ice can be an active source or sink for CO_2 (e.g., Miller et al. 2011; Nomura et al. 2010). However, the magnitude of these processes is not clear. The objective of this fieldwork is to follow the change of carbonate system as well as phosphate concentration during the sea ice growth and decay using our newly developed sea ice DIC sampling technique. Focus will be particularly on the transition between ice growth and ice melting, to understand the response of the carbonate system during this transition.

Measurement of bidirectional reflectance distribution function of sea ice using Gonio-Radiometric Spectrometer System (GRASS) – Collaborative project with David Barber, M. Lamare (Royal Holloway University of London), M. King (RHL, University of London, UK), and C. Greenwall (National Physical Laboratory, UK)

In this project, we will measure multi-angular reflectance, also known as bidirectional reflectance distribution function (BRDF) of bare sea ice at the SERF facility. To do so, the team will deploy GRASS (Gonio-Radiometric Spectrometer System), an instrument that records quasi-simultaneous, multi-angle, hyperspectral measurements of the Earth's surface reflectance. The main objectives of the project is to obtain a full BRDF dataset of bare sea ice, using the sun as a natural illumination source. The BRDF will be obtained as a function of solar zenith angle and ice thickness. Satellite observations are ideal for the synoptic observation of expansive and inaccessible areas, serving as both primary and secondary sources of information. However, global observing systems and in particular studies requiring different spatial resolutions and long time bases require accurate knowledge of sensor to sensor biases. Therefore the responsivities of all optical radiometers operated in space need to be intercompared and traceable to a common reference standard. CEOS (Committee on Earth Observing Satellites) has established a number of Earth targets to serve as international reference standards, such as polar sea ice and snow, needing to be well characterized by surface based in-situ measurements. The reflectance of natural surfaces being non-isotropic, knowing the bidirectional reflectance distribution function (BRDF) of natural surfaces is a pre-requisite for the use of satellite data.

CCGS Amundsen -Canadian Arctic- 2015

Industry Partnership with Statoil - Oceanic and Atmospheric Forcing of Sea Ice Dynamic and Thermodynamic Processes- Project led by David Barber with collaboration from Tim Papakyriakou and Lauren Candlish

The objectives of this study were to provide information on the oceanic and atmospheric forcing data of sea ice floes off the Newfoundland Coast in the Labrador Sea, upstream from areas of interest in the Flemish Pass. Data was to be collected on sea ice motion using GPS position only beacons (POB). The beacons were to be coupled with small surface meteorological stations (SMS) that would measure wind speed and direction and surface pressure. At one station an Acoustic Doppler Current Profiler (ADCP) was to be installed to monitor shallow under-ice currents. These shallow data would be supplemented by deeper current fields recorded using the Amundsen's ADCP. Unfortunately due to unfavourable sea ice conditions the field project was only able to collect one sea ice sample. The ice foes were generally too small and weak to deploy any personnel. The remainder of the data was collected while the ship was underway using the atmospheric instruments that we installed on the CCGS *Amundsen*.

Industry Partnership with ExxonMobil and IOL - Oceanic and Atmospheric Forcing of Sea Ice in the Beaufort Sea - Project led by David Barber and Lauren Candlish

This project looked at the interactions between the ocean, sea ice and lower atmosphere. In order to accurately predict the movement of sea ice and ice break-up accurate estimates of surface winds are needed. During late August and early September, three on ice meteorological towers were deployed in the Beaufort Sea collecting near surface winds, temperature, humidity and pressure. One met tower was lost about a month after deployment likely due to ice deformation. The remaining two met towers will collect data on the ice for ideally 6 – 12 months. The in-situ data will be compared to different forecasted and re-analysis datasets to evaluate the current understanding and ability to correctly forecast or model winds in the high Arctic. Using in situ observations of ice drift, surface winds and ocean currents we will determine how ice drift and forcing change as the icepack progresses from free drift in summer to restricted motion in a consolidated icepack.

ASP Field Programs -Station Nord, Greenland-2015

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

This project studied the spatial and temporal variability of the landfast ice around Station Nord. Two autonomous ice mass balance buoys were deployed in conjunction with moorings during the late winter early spring. These instruments record air, ice, snow and water temperatures, air pressure, surface winds, snow depth and ice thickness for one year. This will reveal the annual cycle and temporal variability of the landfast multiyear ice pack around Station Nord. The spatial variability of ice thickness and snow depth was sampled in conjunction with the CTD transects, during which an Electromagnetic Induction system and a Ground Penetrating Radar system was be towed behind sleds. Repeat sampling of these transects occurred during later legs of the field program to supplement observations of the seasonal melt around Station Nord. Coordinated airborne surveys by Operation IceBridge and the Alfred Wegner Institute will expand our observations, while our on the ice sampling will be used to validate and improve the accuracy of these large international projects.

Sea Ice Geochemistry – Mercury Ikaite and phosphate - Collaborative project with David Barber, Yubin Hu, Fei Wang and Soren Rysgaard

This project looked at mercury transport across the snow-sea ice-ocean interface in first-year and multi-year sea ice, with a particular emphasis on the potential production of methyl mercury in sea ice. The project also studied the vertical distribution if ikaite crystal within sea ice as well as the amount of phosphate co-precipitated with ikaite.

Melt pond sampling was carried out on an ice floe for both carbonate system and mercury study. We also did a lot of water sampling along the glacier tongue. We found interesting seawater pH gradients along the glacier tongue, which might be caused by the runoff from glaciers. This will be further confirmed by analyzing the water samples (DIC, TA etc) brought back in Winnipeg.

Sediment distributions and characteristics in seawater, sea ice and glacier ice -Project led by Jens Ehn

The objective of this project is to describe the distribution and characteristics of the sediments found in the glacier ice, water column and sea ice, and to determine the physical mechanisms involved. In conjunction with oceanographic and ice thermodynamic sampling, this project relies on optical methods to determine the concentration, size distribution and absorption of the particle assemblages found in the three media: seawater, sea ice, and glacier ice.

Samples were taken from multiyear ice melt ponds, under ice water, surface ice, cryoconite hole and ice core samples that were analyzed for particulate dry mass, spectral absorption and size distribution. The sea ice work was all conducted on the multiyear ice floe located just northwest of the station. Water column observations were focused on transect sampling in the area to the east of the station where a major outlet glacier of Flade Isblink terminates.

We observed notable changes in the water column hydrography related to ice and glacier melting and radiative heating which clearly influenced the optical properties and suspended particulate matter distributions in the area. Optical sampling included transects of vertical profiles with a Satlantic HyperOCR free falling profiler and a Sequoia LISST 100X in addition to taking water samples with a Niskin bottle. More frequent optical sampling obtained with the CTD, which included PAR and turbidity sensors.

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

The major objective of this project was to collect oceanographic data and consider the physical mechanisms that potentially impact the landfast sea ice and tidewater glaciers (and vice versa) in the Station North region. Relatively warm intermediate North Atlantic waters can be found at intermediate depths off the NE Greenland continental slope. These waters might penetrate along the submarine troughs and valleys into the shallow coastal areas where vertical mixing processes could initiate heat transport to the lower surface of sea ice. The impact of this heat on the sea-ice thermodynamic growth, brine rejection, buoyancy-driven mixing and the gas exchange will be studied. The tidewater glaciers might be even ablated directly at intermediate depths depending on local bathymetry that is currently unknown. Both short-term mooring deployments in the vicinity of the glacier-ocean contact zone, and long-term mooring observation under the land fast ice are selected as project priorities.

The project started in April 2015 with a regional oceanographic CTD survey (including the glacier area) and the installation of an Ice Tethered Profiler (ITP) CTD in the vicinity of glacier-ocean contact zone. In addition, ADCP measurements, microstructure turbulence measurements and water sampling below the land-fast ice were executed. An array of three moorings, between the Prinsesse Margrethe Island and Prinsesse Thyra Island, equipped with an ADCP/CTD/ITP, were installed near the ice mass balance buoys (described above) and will be retrieved during the 2016 field campaign.

GreenEdge, NOW -Baffin Bay- 2015

Bio-optical characterization of under-ice primary producers – collaborative project between CJ Mundy and Jens Ehn

This project examined the processes influencing spectral light transmission through a melting ice-covered water column in order to improve our understanding on how a warming Arctic could affect primary production in the future. In situ light transmission profiles of upwelling and downwelling spectral irradiance were conducted to estimate spectral light transmission and water column diffuse attenuation. These profiles were made under a variety of different types (snow-covered, drained ice, and melt ponds) in order to characterize the under-ice light field as the system proceeds through different melt stages. Through analyses of these in situ data as well as detailed bio-optical properties measured on discrete depth water samples, we are able to investigate the spatiotemporal variability of the system and quantify the influence of primary producers on the under-ice light climate.

The GreenEdge project was listed in our ArcticNet proposal, however due to budget cuts to the proposal the participation in this field project was fully funded by alternative sources.

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

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

One of the goals of this project was to conduct collaborative research activities and develop strong lines of communication with the communities in the Belcher Islands. The information gathered will be relative to the Hudson Bay IRIS and will promote knowledge exchange between the researchers and the communities. The winter 2016 field program was designed based on the highly successful 2015 field program, where transect lines of CTDs were performed on land fast ice near the communities of Inukjuak, Umiujaq, Kuujjuaraapik and Chisasibi. Master's student Annie Eastwood's was partially funded through this ArcticNet project to participate in the field campaign.

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

Conferences, publications and disseminating our results.

- Lauren Candlish and David Barber led the climate chapter for the Beaufort Sea IRIS, which was published in 2015. As part of this report they updated the climatologies of the atmosphere and sea ice for the region and did statistical analysis on the associated trends.
- The study by Andrews et al. (2016) is a direct contribution to the Hudson Bay IRIS and is being incorporated into several chapters of the document.
- We have 45 peer-reviewed publications from this past year in over 20 different national and international journals.
- As part of our community engagement we have participated in the following meetings that are at a local, provincial and national level:
    - David Barber, Lauren Candlish, Jonathan Andrews and Claire Hornby presented to the community leaders of Hudson Bay at the Hudson Bay Regional Roundtable meeting in April 2015 and again in February 2016.
    - David Barber presented at the Fisheries Joint Management Committee Meeting, Spring 2015, Inuvik.
    - David Barber presented to the Minister of Environment, May 2015, Ottawa.
    - David Barber participated in the CHARS advisory committee meeting, May 2015, Ottawa.
    - David Barber presented to the Province of Manitoba Water Resources, May 2015, Winnipeg.
    - David Barber presented to the Premier of Manitoba on the CMO project, June 2015, Winnipeg.
- David Barber hosted the AMAP-SWIPA Workshop in Winnipeg in February 2016.

- Scientific presentations were made at the following meetings and conferences:
  - » GRC, Spring 2015, Italy
  - » ArcticNet ASM, Dec 2015, Vancouver
  - » Eastern Snow Conference, Summer 2015, Quebec
  - » ACUNS International Student Conference, Nov 2015, Calgary
  - » AGU, Fall 2015, San Francisco
  - » European Space Agency, Spring 2015, Italy
  - » European Space Agency, Sept 2015, Poland
  - » Network of Expertise on Transportation in Arctic Waters, 3rd workshop, Aug 2015, Iqualuit
  - » The Wildlife Society 22nd Annual Conference, Oct 2015, Winnipeg
  - » Forum for Arctic Modelling and Observational Synthesis, Nov 2015, Hyannis, Massachusetts
  - » Warming of the North: Challenges and Opportunities for Arctic Transportation Supply Chain Management, & Economic Development, Spring 2015, Ottawa
  - » IGARSS, Summer 2015, Italy
- Students from our group participated in the annual Schools on Board and Fort Whyte Alive - Arctic Science Day in February 2016. 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).

RESULTS

During the past fiscal year (April 2105 – March 2016) we have produced 45 peer-reviewed publications. We have also presented at over a dozen different international conferences. Due to space restrictions, this section highlights only a small portion of our recent results.

Hudson Bay Analysis

Hudson Bay's sea surface salinity has been analyzed by Nathalie Theriault as part of the BaySys and Hudson Bay IRIS projects. Figure 1 shows a map of ocean surface salinity at Week Of Year 39 (Sep 24th-30th) from years 2010 to 2014. The salinity data comes from the Soil Moisture and Ocean Salinity (SMOS) satellite and were provided by the European Space Agency. All satellite passes were averaged over a week in order to diminish the number of missing data. These weekly maps are used to look at inter-annual variability of ocean surface salinity before the ice starts to form.

Figure 2 (created by Nathalie Theriault) shows a time series of freshwater runoff data for 17 rivers with outlets into Hudson Bay. Data are available from years 1980 to 2013, they are interpolated by Déry et al. (2011) from the online HYdrometric DATabase

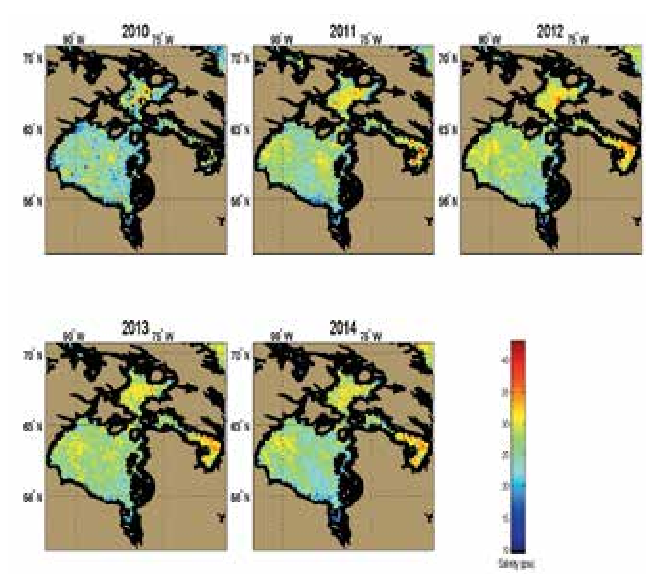

Figure 1. The sea surface salinity for Hudson Bay during the week of September 24-30 for each of the years between 2010 and 2014.

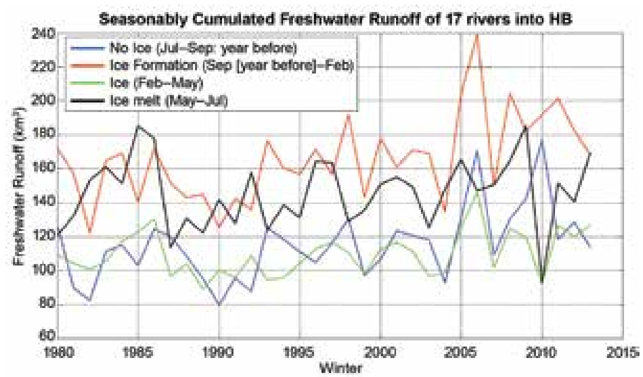

Figure 2. The seasonal accumulation of freshwater runoff for 17 rivers with outlets into Hudson Bay for the years 1980 - 2013.

(HYDAT). The rivers that are included in the analysis are: Broadback, Grande Baleine, Nastapoca, Nottaway, Pontax, Moose, Albany, Attawapiskat, Ekwan, Severn, Winisk, ChesterfieldInlet, Thlewiaza, Churchill, Hayes, Nelson, and Seal. This time series is used to better understand intra- and inter-annual variability of freshwater runoff and will be compared to weekly Sea Ice Concentration data in order to investigate its potential impact.

Climate Change in the Hudson Bay Complex: Opportunities and Vulnerabilities for the Port of Churchill's Marine Operations

Andrews et al. (2016) led a project, which looked at the impact of climate change in Hudson Bay, Hudson Strait, and Foxe Basin, and to examine the resultant vulnerabilities and opportunities for the Port of Churchill's marine operations extending to 2030 and 2050. Changes in sea ice and their consequences for shipping routes are of particular interest. The Port of Churchill is an international port located on the southwest coast of Hudson Bay in Churchill, Manitoba. The Port's primary freight is Canadian grain and roughly 500,000 tonnes of grain are exported to international destinations each year. Shipping vessels travelling to the Port of Churchill pass through Hudson Strait and into Hudson Bay. The Port of Churchill is physically accessible to shipping traffic only during an open water season that currently runs from roughly mid-July to early November. The Port is striving to increase its annual grain shipments and may begin to ship potash or oil on a large scale within the time frame that we focus on (2030 and 2050). Marine re-supply activity through the Port could also increase in response to the growth of communities and industry in the Hudson Bay Complex. Moreover, these potential changes at the Port are occurring alongside dramatic changes in the climate and environment of the Hudson Bay Complex.

The Complex is a highly dynamic environment undergoing rapid change. The Complex currently experiences surface air temperatures that range from seasonal averages of -10 to -30˚C in the winter and 0 to 12˚C in the summer. The seasonal climatology (1979-2013) of surface air temperatures over the Hudson Bay Complex from NCEP reanalysis is shown in Figure 3. These temperatures are warming rapidly in all areas of the Complex, particularly in the fall. This warming is expected to continue into the future, with projections calling for an increase of nearly 1˚C per decade in the annual average temperature of the Complex between 2012 and 2061.

At present the Hudson Bay Complex is largely ice free during the months of August, September, and October, with the longest open water season occurring in Hudson Bay, followed by Hudson Strait, and Foxe Basin. The open water season has grown significantly in all three regions of the Complex since 1980, with break-up occurring earlier and freeze-up moving later into the fall. Climate projections predict that these changes will continue at pace or more rapidly in the future.

Storms are most frequent, intense, and lengthy in the Complex during the "storm season" of August to December. This "storm season" appears to be extending into the winter in response to longer open water conditions. Although there is little evidence of change in monthly average snow and rain fall at Churchill since 1970, there was an observable shift towards increasing daily precipitation earlier in the shipping season and lower daily precipitation later

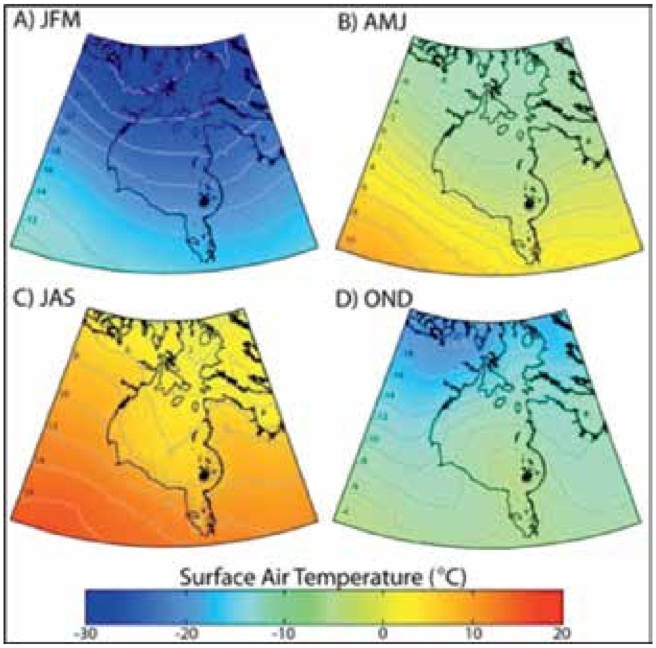

Figure 3. Average seasonal surface air temperatures for the Hudson Bay Complex between 1979 and 2013 according to NCEP reanalysis data. Winter – January, February, and March (JFM); Spring – April, May, and June (AMJ); Summer – July, August, and September (JAS); Fall – October, November, and December (OND).

in the season. Freezing precipitation, meanwhile, is responding in highly variable fashion to changes in climate while the frequencies of fog and blowing snow are largely declining in the Complex. Finally, average winds are strongest in the fall in the Hudson Bay Complex and many areas, including Churchill, have experienced an increase in wind speeds since 1970.

Albedo feedback enhanced by smoother Arctic sea ice

Landy et al. (2015) developed an empirical model that can predict melt pond fraction on sea ice from measurements of the pre-melt sea ice surface roughness. The ICESat operational period 2003–2008 coincided with a dramatic decline in Arctic sea ice—linked to prolonged melt season duration and enhanced melt pond coverage. Although melt ponds evolve in stages, sea ice with smoother surface topography typically allows the pond water to spread over a wider area, reducing the ice-albedo and accelerating further melt. Landy et al. (2015) developed this theory into a quantitative relationship between pre-melt sea ice surface roughness and summer melt pond coverage. The method, applied to ICESat observations of the end-of-winter sea ice roughness, can account for 85% of the variance in advanced very high resolution radiometer (AVHRR) observations of the summer ice-albedo. An Arctic-wide reduction in sea ice roughness from 2003 to 2008 explains a drop in ice-albedo that resulted in a 16% increase in solar heat input to the sea ice cover, which represents ten times the heat input contributed by earlier melt onset timing over the same period. Figure 4 shows the results of the model on Arctic-wide maps. The comparison of the model predictions and the observed AVHRR surface albedo are shown in the third column (e & f).

Identifying Changes in the Formation and Dissolution of the North Water Polynya

Stark et al. (2016) used a 34-year passive microwave sea ice concentration dataset to examine the variability of the Smith Sound ice arch associated with formation and dissolution of the North Water Polynya (NOW) from 1979-2012. An index classification algorithm was generated to determine the presence or absence of the Smith Sound ice arch using an 80% sea ice concentration threshold. The algorithm focused on two points of interest: Kane Basin, which had a known sea ice concentration during winter, and northern Baffin Bay, which was situated in the open water of the polynya. Results show that several years were characterized by anomalous behaviour, including the polynya forming earlier (2003 and 2006), the ice arch not forming in Smith Sound (1983, 1990, 2009), and the ice arch not forming at all (1993, 1995, 2007, 2010) (Figure 5). The algorithm results indicated a shift in the timing of polynya formation and dissolution, with both occurring earlier. Formation of the polynya occurred 18 days earlier by the end of the study period, while dissolution occurred 17 days earlier. These shifts are speculated to be a response to the changing Arctic system. The implications of the timing of formation and dissolution are important when considering the physical, biological, and geochemical implications of changing ice conditions in the NOW polynya.

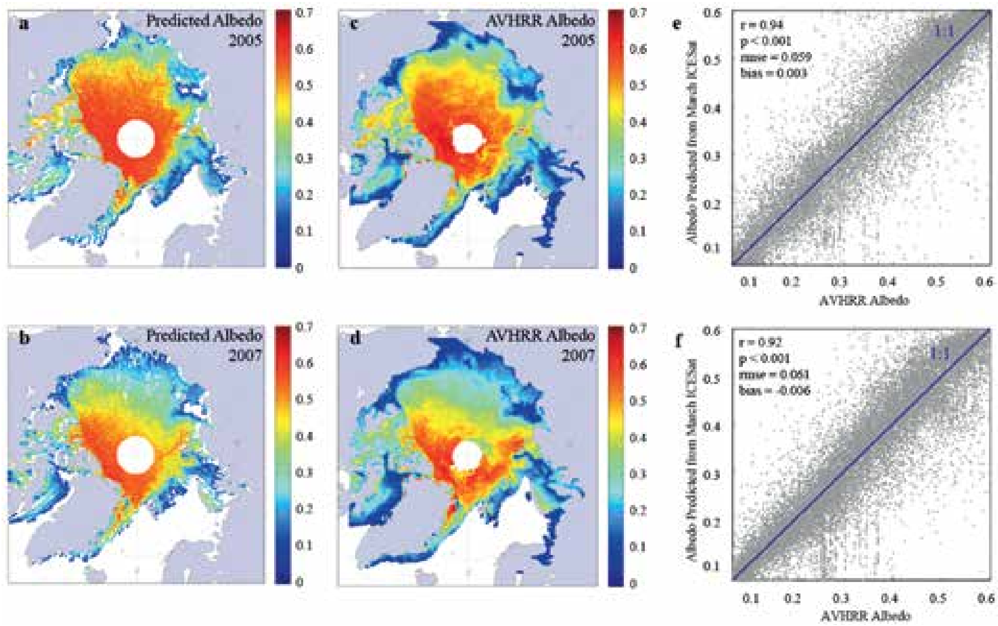

Figure 4. (a and b) Predicted shortwave albedo in June–August, based on empirical model estimates of fp for the hnet integral from 20 to 40 mm, and using ICESat roughness observations in March and AMSR-E sea ice concentration. (c and d) Observed shortwave albedo in June–August, from AVHRR. (e and f) Comparison between predicted and observed surface albedo. One-to-one lines are highlighted in blue. Figure from Landy et al. (2015). © 2015, John Wiley and Sons. © 2015 American Geophysical Union. All Rights Reserved.

On sea-ice dynamical regimes in the Arctic Ocean

In the study by Luckovich et al. (2015) they address spatio-temporal coupling from the perspective of single-particle dispersion statistics to identify coherent ice-drift features characteristic of distinct dynamical regimes. Figure 6 shows temporal scaling of sea ice dynamics based on SEDNA (Hucthings and Hibler, 2008) campaign for zonal, meridional, and total absolute dispersion and elapsed time. Different scaling laws are observed for the perennial ice zone and seasonal ice zone at the same time of year.

Retrieval of Young Snow-Covered Sea Ice Temperature and Salinity Evolution through Radar Cross Section Inversion

Firoozy et al. (2015b) utilized an electromagnetic inverse-scattering algorithm to quantitatively reconstruct the vertical temperature and salinity profiles of snow-covered sea ice from time-series monostatic polarimetric normalized radar cross-section (NRCS) data. The reconstructed profile at a given time step is utilized to provide *a priori* information for the profile reconstruction at the subsequent time step. This successive use of *a priori* information in the inversion algorithm results in achieving high reconstruction accuracy over the time period of interest. This inversion scheme is evaluated against the experimental data collected from snow-covered sea ice grown in an Arctic ocean mesocosm facility. It was shown that the time evolution of the temperature, salinity, and density profiles of an artificially grown snow-covered sea ice can be quantitatively reconstructed using single-frequency time-series radar cross-section data assuming that these profiles are initially known with sufficient accuracy. Figure 7 depicts the reconstructed profiles.

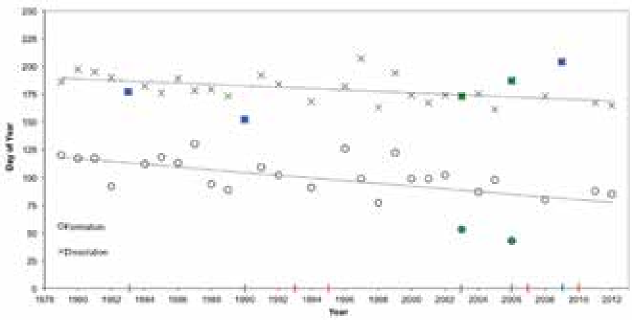

Figure 5. Formation and dissolution of NOW determined by the index classification algorithm. Red markers indicate years with no ice arch, blue markers indicate no ice arch in Smith Sound, and green makers indicate early formation years. The years of no ice arch in Smith Sound have dissolution days because the SIC at P1 was <80%, indicating there was an arch elsewhere in Nares Strait.

DISCUSSION

Climate Change in the Hudson Bay Complex: Opportunities and Vulnerabilities for the Port of Churchill's Marine Operations

The Port of Churchill's shipping operations are vulnerable to adverse weather in the Hudson Bay Complex and these operations may be rendered more vulnerable by a lack of hydrographic data for the Complex and by the Coast Guard's limited Search and Rescue capability in the area.

Adverse weather that could impact the Port's operations and transportation and shipping in Hudson Bay includes high winds, precipitation, and storms. Wind may currently interfere with Port operations during roughly half of the days in the shipping season and projections for the future suggest that wind disruption could become more common. As for precipitation, roughly half the days of the shipping season pass without measurable precipitation and there is a general tendency towards an increasing risk of precipitation disruption in the early months of the season and a declining risk of precipitation disruption in the later part of the season. Finally, the current storm regime may disrupt shipping related operations at the Port and within the Complex for 10 to 18 days of the shipping season and there does not appear to be projections for significant change to this regime.

The open water period along the direct shipping route to the Port of Churchill averaged 16.3 weeks in length from 1980-2010 and will likely extend beyond a minimum of 18.4 weeks by 2030 and 20.4 weeks by 2050. Model projections are in fact calling for an open water season of closer to 30 weeks by 2050. Meanwhile, current and projected environmental and economic conditions in the Hudson Bay Complex are highly favourable for an expansion of the Port of Churchill's re-supply activity.

The ecosystems of the Hudson Bay Complex are vulnerable to a variety of stressors produced by Port and shipping operations. The most pressing vulnerabilities include pollution, disturbance of marine mammals, and the introduction of invasive species. With regard to pollution, the Hudson Bay Complex appears to be particularly vulnerable to a potential oil spill.

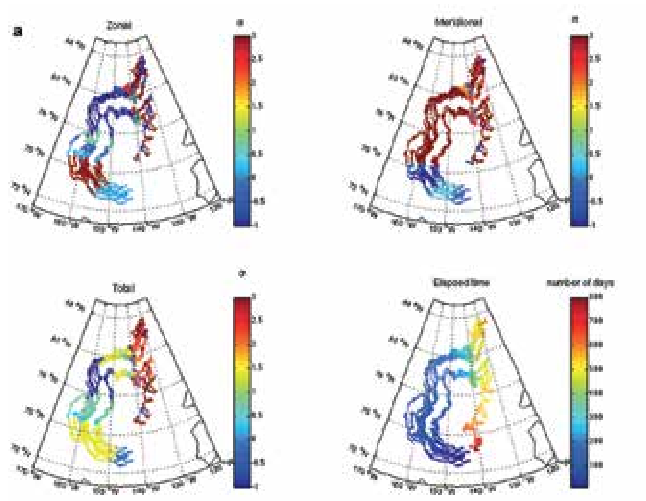

Figure 6. Temporal scaling maps for zonal, meridional and total absolute dispersion (with scaling intervals defined according to absolute dispersion critical points), in addition to elapsed time (days), for duration of the experiment for all SEDNA buoys.

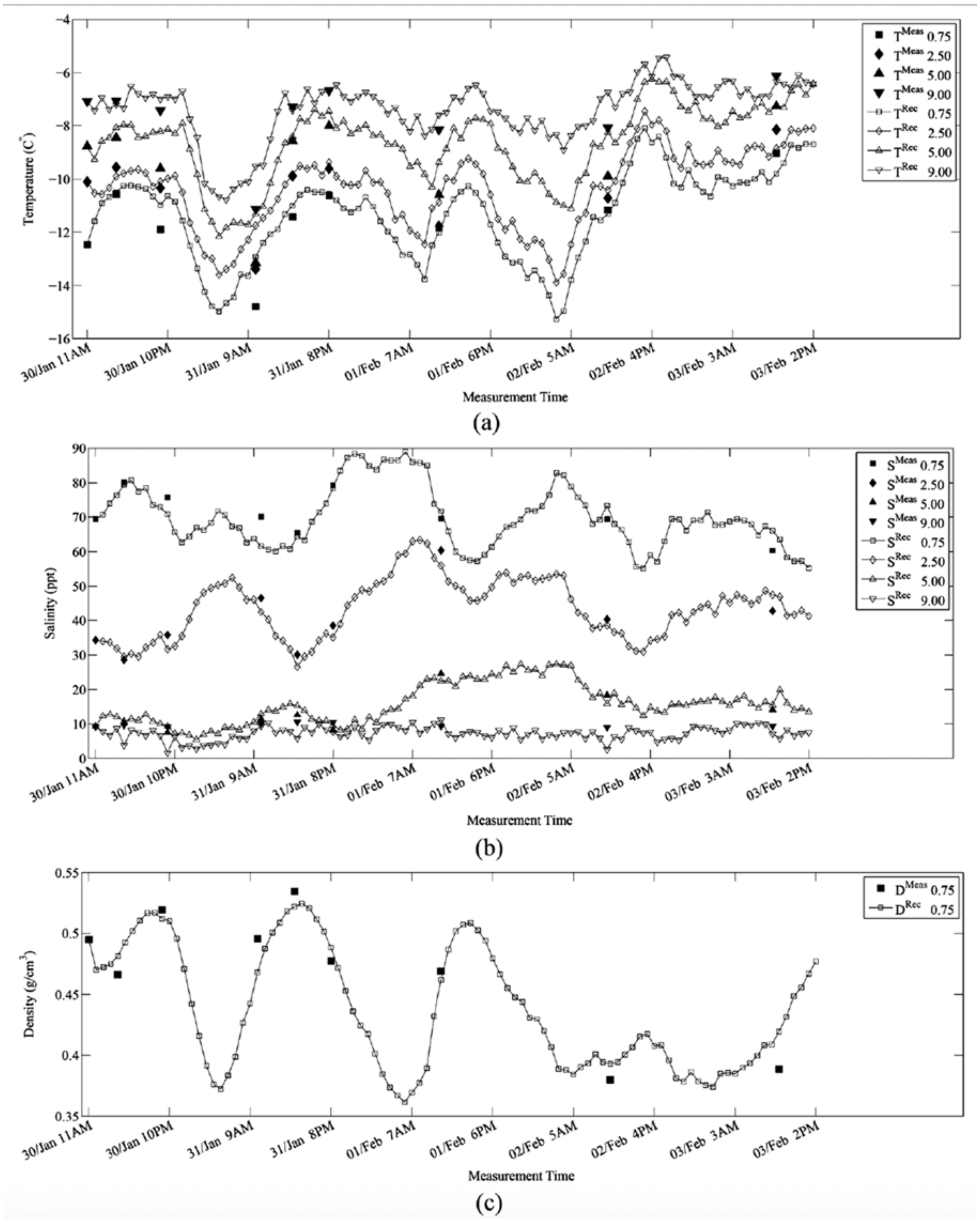

Figure 7. Time-series reconstruction results from January 30th 11am to February 3nd 2pm for the (top panel) Temperature profile; (middle panel) Salinity Profile; and (bottom panel) Top layer (slush) density profile. Depth is given in cm. Rec and Meas stand for reconstructed and measured data.

Albedo feedback enhanced by smoother Arctic sea ice

The conclusions of Landy et al. (2015b) reveal the possibility for an interannual feedback loop between winter sea ice roughness and summer surface melt. Summer melting either reduces the thickness of the ice cover or causes it to disappear completely. Although ICESat laser altimeter observations demonstrate that sea ice surface roughness can vary considerably within FYI or MYI zones, FYI is generally smoother than MYI over local scales (Rivas et al., 2006). Therefore, if relatively thin new ice replaces thicker older ice in winter, following a summer of enhanced melting, the overall roughness of the sea ice topography will decrease. Our results have shown that melt pond coverage is higher on seasonal ice with smoother surface topography, so the albedo of the thinner and smoother ice cover will be reduced in the subsequent summer, further enhancing the rate of ice melt. Satellite observations have shown that MYI is being progressively replaced by FYI within the Arctic basin (Comiso, 2012; Maslanik et al., 2011; Stroeve et al., 2012), which is potentially both a consequence of, and contributes to, the proposed feedback loop.

Identifying Changes in the Formation and Dissolution of the North Water Polynya

Stark et al. (2016) developed an index classification algorithm to generate a universal method that would classify the dynamics of multiple polynya types using a passive microwave dataset. To better understand the seasonality of NOW, Stark et al. (2016) divided the output from the model into 4 distinct seasons: winter, formation, dissolution, and fall freeze-up. The length of each season is a direct result of the local conditions in a given year. No two years of polynya formation and dissolution were the same, confirming that NOW is influenced by multiple factors. The presence of atypical years, especially when the ice arch did not form at Smith Sound, shows how the ice arch responds to changes in the dominant ice pack in Nares Strait (Kowk et al., 2005; Kwok et al., 2010) and decreases in the overall Arctic ice extent (Cavellieri and Parkinson, 2012).

On sea-ice dynamical regimes in the Arctic Ocean

Central to an understanding of evolution in sea-ice characteristics in response to climate change is an understanding of sea-ice dynamics. This includes the accompanying implications for ocean–atmosphere heat and moisture exchange associated with the development of leads and polynyas, freshwater transport associated with changes in ice drift, and ice-drift response to relative changes in ice age, thickness and regional atmospheric circulation. An accurate representation of sea-ice drift and deformation is essential in modeling ocean–sea-ice–atmosphere interactions, nutrient and contaminant transport in ice-covered waters, and in ice hazard assessments relevant to shipping and transportation. Luckovich et al. (2015) investigated spatio-temporal characteristics of sea ice drift and state through development of temporal scaling maps to quantify distinct dynamical regimes using partical statistics. Results from this investigation highlight regional differences in absolute dispersion statistics, scaling laws and temporal scaling maps for the surrounding Beaufort region and the interior of the Beaufort Gyre, and within the PIZ and SIZ ice regimes. We can use information from this analysis to map diffusive, super- and sub-diffusive regimes and, in particular, regions of ice that are shearing, in free drift, and under compaction together with the magnitude of dispersion. The results from this analysis provide an alternative characterization to changes in sea ice based on dynamics rather than concentration and thickness, and thus insight into, and improved understanding of, the connections between sea-ice drift and morphology.

Retrieval of Young Snow-Covered Sea Ice Temperature and Salinity Evolution through Radar Cross Section Inversion

During January and February 2015, Firoozy et al. (2015b) performed a series of remote sensing experiments at the Sea-ice Environmental Research Facility (SERF), located at the University of Manitoba. During this experiment, the young sea ice was artificially grown, and its associated time-series normalized radar cross section (NRCS) data were collected through a C-band scatterometer. Temporal physical sampling of the growing sea ice was performed to determine the dielectric properties of the medium. The objective of this experiment was to establish a correspondence between the NRCS associated with the young sea ice, with its dielectric/thermodynamic properties. This was achieved through the so-called electromagnetic inverse scattering algorithm. This algorithm takes in the NRCS data as its input, and retrieves the properties of interest, i.e., temperature, salinity, and density of the top 9 cm of ice and also the thin snow layer. The retrieved values are in agreement with in-situ measured parameters. These parameters are of significant importance as they can be fed to Arctic climate prediction models.

Since the developed algorithm only utilizes a single-frequency time-series monostatic NRCS data, it has the potential to be extended to time-series SAR data inversion for quantitative monitoring of a given investigation domain. To this end, it needs to be ensured that an accurate retrieval at the first time step is available to the inversion algorithm. In practice, this might be achieved by employing ground truth exploration, or inverting more informative data at the first time step (e.g., the data collected from an airborne multifrequency multipolarization SAR platform).

CONCLUSION

The Arctic climate is closely tied to the state of the cryosphere. Our research is driven by our desire to improve our collective understanding of the interactions that occur between the ocean, the sea ice and the atmosphere and the consequences of the changing climate on the biological and biogeochemical processes in the marine environment. 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 agencies. Below is a summary of the contributions from April 2015-March 2016 to our overall objectives.

1. Macro-scale

- Nathalie Theriault, David Babb and Jonathan Andrews have produced climatologies of the ocean and sea ice for Hudson Bay that are going to be direct inputs into the Hudson Bay IRIS.
- Stark et al. (2016) looked at the formation and dissolution of the North Water Polynya to determine the spatial and temporal variability of the Smith Sound ice arch.
- Luckovich et al. (2015) contributed to our understanding of dynamic sea ice regimes at the macro-level in the Beaufort Sea.
- Other examples of studying the system at a regional to hemispheric scale include: Asplin et al. (2015); Candlish et al. (2015); Babb et al. (2015); Barber et al. (2015); Ogi et al. (2015); Luckovich et al. (2015).
- We've looked at the Arctic system at a more local to regional scale with examples such as Raddatz et al. (2015a,b); Dmintrenko (2015a, 2015b); Stark et al. (2016); Killirov et al. (2015) Haas and Howell (2015) and Jackson et al. (2015).

2. Micro-scale

- In contribution to our micro-scale objective we collaborated with Soren Rysguaard and Yubin Hu with the Greenland project on the carbonate system and phosphate evolution during sea ice growth and decay and the SERF project on sea ice geochemistry for mercury ikaite and phosphate.
- Our group has also investigated the exchange processes at the micro- to local-scale of mass and energy across the OSA interface, examples include Raddatz et al.(2015c); Galley et al. (2015a,b,c); and Sievers et al. (2015).

3. Community-Based Monitoring (CBM)

- We helped support the community-based monitoring project in the Belcher Islands during the 2016 field season.

- Annie Eastwood presented her results from 2014 and 2015 field seasons in the Belcher Islands at the ArcticNet annual meeting in December 2015.

4. Technology

- In contribution towards our technology objective we have developed an empirical model that can predict melt pond fraction (Landy et al. 2015b).
- Publications by Firoozy et al. (2015a, 2015b and 2015c) used microwave remote sensing data of sea ice to further develop and refine inverse scattering models.
- Our group has also investigated microwave remote sensing of snow covered sea ice (Nandan et al. 2015; Gill et al. 2015; Fuller et al. 2015a,b; Casey et al. 2015).
- In contribution to our technology objective we collaborated with researchers from Roma Tre University, Italy to look at sea ice physical properties using Multilevel Transmission Lines and Ground Penetrating Radar (GPR) during the second experimental phase in winter 2016 at SERF.
- We have also collaborated with researchers from the University of London and National Physical Laboratory, UK, to look at the bidirectional reflectance distribution function of sea ice using Gonio-Radiometric Spectrometer System (GRASS) during the second experimental phase in winter 2016 at SERF.

Through our many studies, in-situ field campaigns and mesocosm studies we have been able to look at the system from a variety of spatio-temporal scales. During the remaining two years of ArcticNet funding we will continue to examine these interacting systems at a range of space and time scales. We anticipate that the continued support from ArcticNet will lead to many more successful future field seasons and the SERF mesocosm studies resulting in numerous peer-reviewed publications.

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Monitoring Marine Biodiversity with eDNA; a New Cost-Effective Method to Track Rapid Arctic Changes

Project Leader

Louis Bernatchez (Université Laval)

Network Investigators

Philippe Archambault (Université du Québec à Rimouski)
Kimberly Howland (Fisheries and Oceans Canada - Freshwater Institute)

Collaborators

Erin Grey (University of Notre Dame)
David Lodge (University of Notre Dame)
Michael Pfrender (University of Notre Dame)

HQP

Anaïs Lacoursière-Roussel, Post-Doctoral Fellow (Université Laval)
Noémie Leduc, Technical Staff (Université Laval)

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

- In the Arctic, climate change and marine invasions are expected to result in high species turnovers. Monitoring large-scale and continuous biodiversity is essential for effective management and conservation plans and ensuring ecosystem sustainability.
- Marine biodiversity monitoring typically requires expensive sampling tools, multiple experts and may cause significant negative impacts on the ecosystem.
- By allowing rapid sample collection, reducing the cost associated with data collection and by not manipulating the organisms, the analysis of environmental DNA (eDNA) could be a revolutionary tool to increase the power of detection, spatial coverage and frequency of sampling.
- This project adapts the eDNA metagenetic method for Arctic marine species and potential invaders.
- A baseline description of Arctic community composition and DNA sequences will be available for future studies.
- By joining an international multidisciplinary network of molecular, invasion and benthic ecologists and policy makers through the Coastal SEES Collaborative Research Network, this project integrates Arctic risk assessments of invasions within global invasion predictive models. This should help to reduce risk of Arctic invasions by integrating an iterative loop of guidance and information between research teams and international shipping policy makers.
- By providing training to local community members and northern research staff, this project address the objectives of working with territorial and federal governments, communities and other funding programs to fill gaps in current research networks, approaches and initiatives.
- This project is co-funded by POLAR and the Nunavut Wildlife Management Board thus expanding the scope to include model development to predict and map current and future risks of nonindigenous species (NIS) associated with shipping and climate warming (identification of high risk pathways, species and geographic locations).
- This co-funded study will provide the foundation for establishing an ongoing NIS monitoring program in the Canadian Arctic through the

development of a community based monitoring (CBM) network/capacity.

OBJECTIVES

We continued to pursue the objectives identified in 2014, at the start of our ArcticNet Phase IV project. Our general objective is to adapt eDNA analysis to Arctic marine ecosystems for detection of biodiversity shifts. These data will offer a cost-effective way to build a long-term standardized benthic and fish biodiversity DNA database in Arctic ports (i.e., similar sampling effort allowing rigorous statistical comparison among sampling sites), which will provide a baseline for rapid detection of Arctic coastal biodiversity shifts (i.e., native species loss/declines, NIS introductions/range expansions).

Goal 1: Surveillance of Coastal Arctic Biodiversity by Metagenomic eDNA Sequencing.

We aim to optimize the effectiveness of the eDNA sequencing approach to capture the broadest metazoan Arctic biodiversity from water samples by:

1. developing a species list reference database of Arctic species and potential aquatic invasive species
2. developing reference DNA sequences
3. evaluating in silico the efficacy of molecular universal primers
4. testing and optimizing the amplification method in vitro on native and potential NIS

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

5. optimize water sampling strategies for eDNA in Arctic marine environments
6. optimize a cost-effective DNA extraction method
7. use the primers developed and tested in Goal 1 to estimate metazoan diversity
8. increasing the accuracy of biodiversity monitoring in the Arctic using eDNA to greatly improve the evaluation of impacts from climate change and long-term human activities in the coastal Canadian Arctic

Goal 3: Establishment of a community based monitoring (CBM) network/capacity:

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

INTRODUCTION

In the Arctic, climate change and marine invasions are expected to result in high species turnovers of over 60% of the present biodiversity with substantial ecological disturbances of marine ecosystems (Cheung et al. 2009). It is also expected to open new waterways in the Arctic Ocean, resulting in greater shipping traffic (ACIA 2004; Niimi 2004; Chan et al. 2012, 2013). Predicted increases in shipping frequency and routes (Smith and Stephenson 2013), increased infrastructure development in ports, and associated chemical and biological pollution will place other ecosystem services at risk. The introduction of undesirable nonindigenous species (NIS) may displace native species, alter community structure and increase fouling of fishing gear, particularly in estuaries and coastal zones. The impact of NIS on industry and society often lead to long-term economic consequences; in Canada, aquatic invasive species directly and indirectly amount to costs between \$13.3 and \$34.5 billion/year (Mack et al. 2000; MEA 2005; Colautti et al. 2006). To mitigate these impacts, policy makers need predictive NIS models to identify high-risk invasion pathways and geographic locations along with monitoring strategies for early detection of species introductions. Monitoring large-scale and continuous biodiversity in the Arctic is essential for effective management and conservation plans and ensuring ecosystem sustainability (Larigauderie et al. 2012). However, heavy and expensive sampling tools (e.g., bottom trawl) are often required, and a large pool of expert taxonomists is necessary for follow-up identification of organisms. This may also limit the capacity of monitoring marine species at large spatial and temporal scales in remote regions. Indeed, many areas of the marine Canadian Arctic and their fauna are still poorly known (Archambault et al. 2010). The lack of consistent biodiversity monitoring, analytical tools, information systems, and reporting makes it difficult to deliver a national-scale ecosystem assessment.

The analysis of environmental DNA (eDNA) could be a revolutionary tool for overcoming the lack of extensive biodiversity data (Taberlet et al. 2012). The eDNA method (distinguishing from DNA or metagenomics which typically refers to genetic material extracted from organisms) is a method that can detect traces of DNA from macro-organisms (e.g., fishes) in cellular or extracellular form in water from sources such as feces, secreted mucous membranes, gametes and skin cells (Haile et al. 2009; Lydolph et al. 2005; Thomsen et al. 2012). The popularity of this method is growing so fast that species inventories collected via eDNA could soon surpass traditional sampling methods (Dejean et al. 2012; Jerde et al. 2011; Pilliod et al. 2013). The frequency of DNA strands may also allow eDNA to provide population abundance information (Takahara et al. 2012; Lacoursière-Roussel et al. 2014, 2015). Thus, using eDNA could allow rapid sample collection, reduce the cost associated with data collection and does not require the manipulation of organisms (Lodge et al. 2012; Taberlet et al. 2012). This method has great potential to increase the power of detection, spatial coverage and frequency of sampling. Integrating eDNA analysis in monitoring of coastal Arctic biodiversity could help standardizing biodiversity monitoring and early detection of species shifts.

Our general objective is to adapt eDNA analysis to Arctic marine ecosystems for detection of biodiversity shifts. This ArcticNet project integrates Canadian Arctic invasive species research within an international network developing predictive, interdisciplinary invasion science capable of informing international policies. As such, this project is a unique opportunity to join the international network, Coastal SEES Collaborative Research: Changes in ship-borne invasions in coupled natural-human systems: infrastructure, global trade, climate and policy. This network, led by D. Lodge, who is also a main collaborator in this proposal, unites world leaders in the development of the eDNA methods and the study of coastal invasions in relation to global shipping, climate, navigation infrastructure, global trade, and policy.

ACTIVITIES

Goal 1. Optimize the effectiveness of the eDNA sequencing approach

It is important to use more than one gene to capture the broadest metazoan Arctic biodiversity. We are testing various primer sets for 18S and COI in silico (i.e. performed via computer simulation), *in vitro* and *in situ* on Arctic specimens and potential invaders (Table 1).

The better our knowledge of local species richness, potential invaders and genetic information, the better will be the calibration of the eDNA method to target potential biodiversity shift (e.g. introduction of invasive species and loss of biodiversity due to the global warming). We thus developed a biodiversity database for surveyed ports and potential invaders obtained from previous surveys (Chan et al. 2012, 2013, Goldsmith 2016; both are collaborators and provided unpublished data to refine our database). Potential Arctic NIS were classified (higher vs. lower risk, hereafter referred NIS-high and NIS respectively) by J. Goldsmith (PhD Thesis) according to the number of barriers they have to introduction and establishment and according to documented information in published articles, grey literature and global invasive species lists available on the web. We developed a reference

Table 1. Primers sequences tested in silico, in vitro and in situ on Arctic native species and potential aquatic invasive species.

Primer name	Primer direction	Gene region	Primer sequence (5´- 3´)	Product size (bp)	Reference
F-574	Forward	18s	GCGGTAATTCCAGCTCCAA	342	Hadziavdic *et al.* 2014
R-952	Reverse	18s	TTGGCAAATGCTTTCGC		Hadziavdic *et al.* 2014
TAReuk454FWD1	Forward	18s	CCAGCASCYGCGGTAATTCC	399	Stoeck *et al.* 2010
TAReukREV3	Reverse	18s	ACTTTCGTTCTTGATYRA		Stoeck *et al.* 2010
mlCOIintF	Forward	COI	GGWACWGGWTGAACWGTWTAYCCYCC	313	Leray *et al.* 2013
jgHCO2198	Reverse	COI	TAIACYTCIGGRTGICCRAARAAYCA		Geller *et al.* 2013
HCO2198	Reverse alternative	COI	TAAACTTCAGGGTGACCAAAAAATCA		Folmer *et al.* 1994
MinibarF1	Forward	COI	TCCACTAATCACAARGATATTGGTAC	130	Meusnier *et al.* 2008
MinibarR1	Reverse	COI	GAAAATCATAATGAAGGCATGAGC		Meusnier *et al.* 2008

DNA sequence library from databases available via public servers (GenBank, SILVA, BOLD/iBOL, SYLVA) and unpublished data from MPO (GRDI and AAFC database) and graduate studies. Most of the Arctic data are not public yet. Kimberley Howland, Philippe Archambault, Chris McKindsey and Anaïs Lacoursière participated to the Canadian Invasive Species Network (CAISN) meeting. CAISN combines 31 researchers from 13 partner universities and six federal laboratories across Canada), to a national network of governments (i.e. Fisheries and Oceans Canada and Transport Canada) and to international (MTB; which currently consists of 25 US and Canadian state and federal officials responsible for policy and/or management of multiple vectors of aquatic invasive species). In addition to presenting our project to the CAISN researchers and getting excellent methodological feedbacks, this meeting allowed us to get unpublished data to build a reference database to calibrate the eDNA method (i.e. pooling data of local biodiversity and COI and 18S sequences for all sampled ports).

To target the best universal primers, a bioinformatic script has been applied to determine whether the primer sequences are present in the sequences of several banks of DNA sequences. This allowed pooling of all public and unpublished sequences database; GenBank (COI and 18S), BOLD (COI), iBOL (COI), SILVA (18S) and Arctic (COI and 18S; unpublished sequences). Searches for primers in the sequence database were performed with python and bash programs developed at the IBIS. The method of regular expression was used as a search algorithm and does not allow for mismatch. The NCBI-BLAST program was also used to confirm certain results. Secondly, we verified if there were any invasive species among the sequences containing the primers. This analysis will ensure that the primer sequences are also absent from prokaryotic genomes that are known to compete strongly in the first PCR reaction cycles and thus preventing the amplification of desired eukaryotic DNA creating false-negative results.

Goal 2. Marine biodiversity shift in Arctic ports

Churchill and Iqaluit ports were sampled in August 2015 (~80 eDNA samples per port). So far, the dispersion of the eDNA in marine waters has never been studied. The eDNA samples were collected at three different depths in sites covering the entire port (N = 13 sites/port, see Figure 1). To assess the effectiveness of the eDNA method for benthic monitoring, corresponding intertidal and subtidal sites were also sampled using classical methods for taxonomy (sediment cores, benthic trawl and grab samples). This will allow us to examine concurrence between classical samples and eDNA samples collected at the same locations. M.Sc. student, Valérie Cypihot (UQAR) was recruited to the project in August 2015; she assisted with field work and will be working with the benthic invertebrate samples as part of her thesis on Arctic coastal benthic ecology. A single shoreline site was also sampled intensively

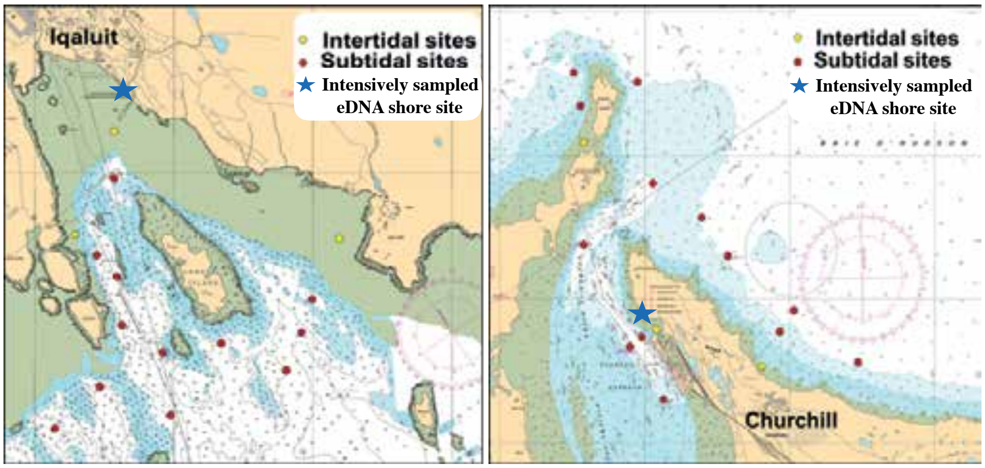

Figure 1. Sites sampled for water quality, eDNA, plankton and benthic invertebrates in 2015-16.

for eDNA (N=20 samples). This site was chosen for its accessibility to allow for (i) comparison to international ports (Coastal SEES Collaborative Research collaboration), (ii) evaluating how many samples are needed to reach the species saturation curve and (iii) future tracking of temporal biodiversity shifts (this site will be sampled each year by northern collaborators).

An efficient eDNA water sampling method for remote regions was developed in the Bernatchez' and Lodge's laboratories. With this method, molecules of eDNA were captured from 250 ml water samples and filtered on glass fibre filters using a syringe filtration technique. Moreover, a new efficient, fast and cheap DNA extraction method has also been developed and tested *in vitro*. To optimize the eDNA extraction, two protocols have been compared (protocol without and with phenol chloroform, mentioned below as protocol A and B respectively). Ten water samples were collected in total (five samples per protocol) and we amplified three qPCR replicates per sample using specific primers and probe.

The DNA amplification method has been optimized *in vitro* on Arctic specimens and potential invaders. PCRs for all eDNA samples should be completed in the next few weeks and the first Illumina MiSeq run will be done mid- February.

Increasing the accuracy of biodiversity monitoring in the Arctic using eDNA will greatly improve the evaluation of impacts from climate change and long-term human activities in the coastal Canadian Arctic. An M.Sc. graduate student, Noémie Leduc (U. Laval), was recruited for the eDNA project. She started her project officially in January, but was hired this fall as a research assistant to learn eDNA laboratory methods and, in this context, has extracted DNA from all samples collected in Summer and Fall 2015. Noémie is seeking to compare Alpha, Beta and Gamma diversity indices between the eDNA and taxonomic data to improve our knowledge about eDNA dispersal and the variability in eDNA efficiency between different taxa.

Goal 3. Community based monitoring network

Training of local community members and permanently stationed northern research staff in basic port survey collection methods and eDNA sampling techniques was conducted in 2015-16. This involved 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. As well local boats and guides were hired in each community. eDNA training workshops were also conducted with Nunavut Arctic College students in twp communities as well as with

HTO members in three communities. Tissue sample kits and identification booklets with descriptions of high risk non-indigenous species were provided to each community for future use.

RESULTS

Goal 1.

To date, our Arctic sequence reference database includes 342 and 212 sequences of Arctic species for the 18S and COI genes respectively (unpublished data provided by Rob Young, PhD Thesis). Specimens that have been collected in the surveyed commercial ports by benthic/fouling organisms collected using cores, grabs and a trawl in the surveyed commercial ports are currently being sequenced (GRDI collaboration) and will be added to our Arctic sequence reference via our developed bioinformatics program (see above).

As expected, more species are amplified in silico using the 18S than COI primers. The TAReuk primers amplified a greater number of Arctic species than the F574-R952 primer sets and the Uni-Minibar did not amplify any of the Arctic specimen in silico (Figure 2a). All 18S primers amplified few bacteria (Figure 2b). For COI, the primer jgHCO2198 amplified bacteria and risk to amplify greater human traces (i.e. undesirable contamination; see primates Figure 2b), but also amplified a larger proportion of species than HCO2198 primer (Figure 2b). In general, both 18S primers amplified all taxonomic groups similarly (Figure 2c), whereas for COI, the forward mlCOIintF and the reverse jgHCO2198 primers were more suitable (i.e. the alternative was less suitable for COI amplification; Figure 2d). Now that the computer program has been developed, we can simulate amplifications with more specific requests, such as species with special Arctic interest, and we can easily integrate sequences of Arctic species that are currently sequenced.

A total of 126 potential invaders —including 13 with high risk to invade— were targeted based on (i) predictive species distribution models (Goldsmith 2016) and/or (ii) ballast waters and ship hull monitoring (Chan et al. 2012, 2013) (see the species list in Appendix 1 bellow). For those species, the 18S primer set TAReuk454FWD1-TAReukREV3 better amplified in silico than F574-R952 (72 vs. 54 potential invaders); only two species amplified with F574-R952 and not with TAReuk454FWD1-TAReukREV3. For the COI primer sets, the mlCOIintF_jgHCO2198 provided better amplification than mlCOIintF_HCO2198 (47 vs. 22 potential invaders).

In vitro - The primer set F-574-R-952 amplified a larger proportion than the TAReuk454FWD1-TAReukREV3 (Table 2). For the COI, the Uni-Minibar primers did not amplify any specimens. The Uni-Minibar primers (Meusnier et al. 2008) would be ideal since they amplify a very short fragment, which can be an important factor for highly deteriorated DNA (130 bp instead of 365 bp). DFO researchers previously had great success with the Uni-Minibar primers to determine the diet of green crabs (potential Arctic NIS). We are currently trying to determine why we do not have success *in silico* and *in vitro* with these primers, and may possibly include them in the future by optimizing the amplification conditions.

Goal 2.

The Arctic samples positively amplified and the Illumina MiSeq run will occur in the next month. We found more eDNA and less variance for samples extracted with protocol B (Ct average = 25.6, SD = 0.35) than protocol A (Ct average = 27.5, SD = 2.52). There was no significant difference in the amount of DNA extracted with the two protocols (t-test, P = 0.09) but there is less variance among samples for the protocol B (t-test, P = 0.03). There was no significant inhibitor effect for both methods (IPC control: 26.99 –27.01, IPC protocol A: 25.69 –26.96, IPC protocol B: 25.53 –26.96).

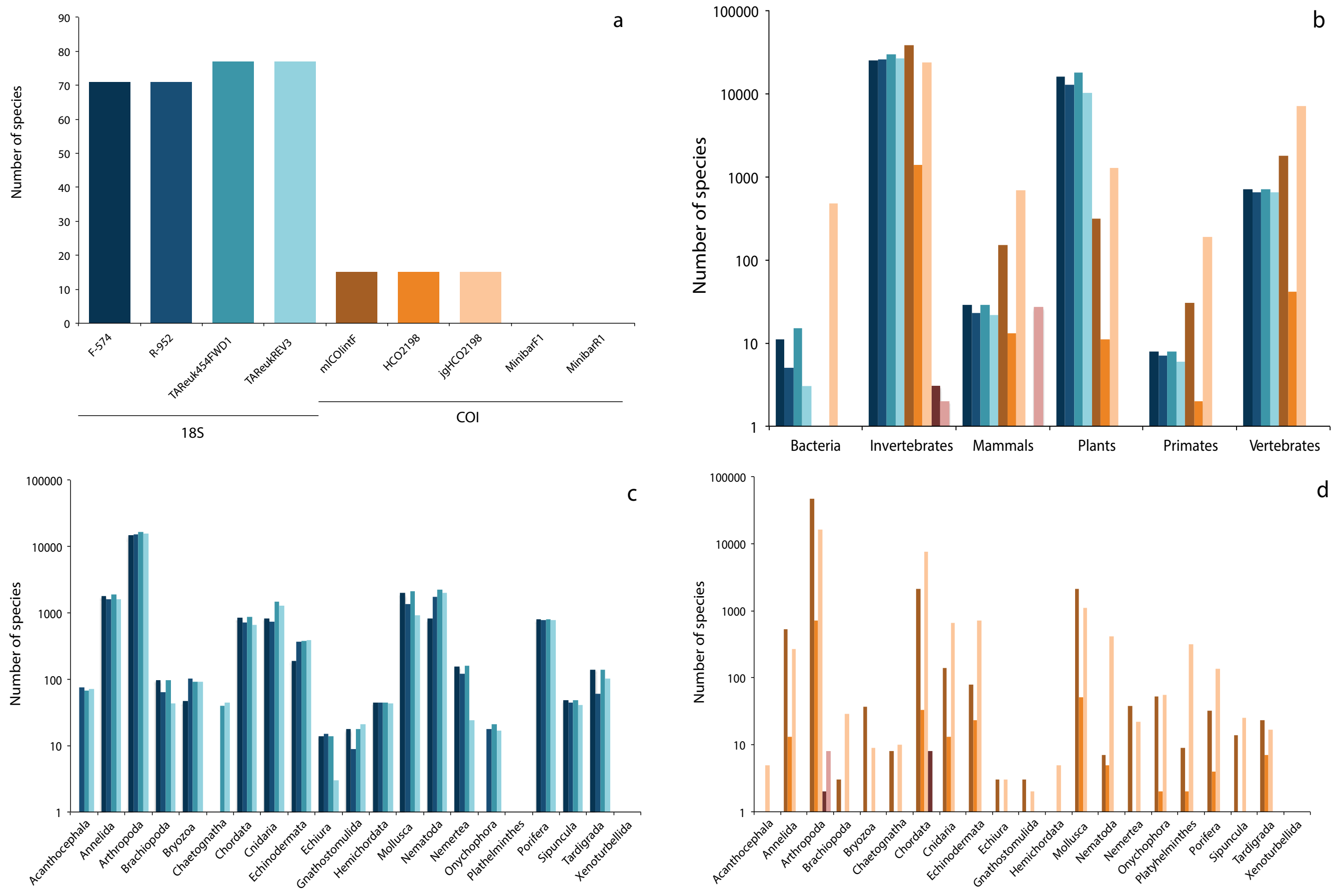

Figure 2. Number of matches amplifying in silico for each primer sets from the dataset of the (a) Arctic species, (b) GenBank (COI and 18S), (c) SILVA (18S) and (d) BOLD/iBOL (COI). Each color depicts a primer shown in 2a, and the dark pink is the Minibar forward and the light pink is the Minibar reverse.

Goal 3.

Hands-on training with various equipment and techniques for port sampling including zooplankton nets, Niskin bottles, water sampling for water quality and eDNA, and boat/beach-based sampling for benthic/fouling organisms using cores, grabs and a trawl was provided to technical staff at the Churchill Northern Studies Center (four people) and we also provided training to a local resident who was a former Parks Junior ranger and interested in environmental monitoring. In Iqaluit, training was provided to local community members (five people) as well as research staff (a training fishery officer stationed in Iqaluit), and a summer student who is a Nunavummiut resident of Iqaluit and pursuing a university degree in marine biology. An introduction to invasion biology and eDNA training workshops were also conducted with Nunavut Arctic College students in Iqaluit and Pond Inlet as well as with HTO and community members in Pond Inlet, Igloolik, Hall Beach and Kangiqsujuak. A hands-on training component was also incorporated into invasive species knowledge transfer workshops in Iqaluit and Kuujjuaq through inclusion of various activities such as specimen collection for bar coding, eDNA collection, and inspection of ballast water. Tissue sample kits and identification booklets with descriptions of high risk non-indigenous species were provided to participants at all workshops and

Table 2. Native species and potential invaders (low and high risk based on Goldsmith (2016) that primers were tested in vitro. '+' depict a positive PCR amplification and '-' that no amplification occurred.

Species	Phylum	Statut	F574 R952	TAReuk454FWD1 TAReukREV3	mlCOIintF jgHCO2198
Gammarus oceanicus	Arthropoda	Native	+	+	+
Astarte elliptica complexe	Mollusca	Native	+	+	-
Musculus discors	Mollusca	Native	+	+	-
Macoma calcarea	Mollusca	Native	+	+	+
Hiatella arctica	Mollusca	Native	+	-	-
Testudinalia testudinalis	Mollusca	Native	+	-	+
Margarites groenlandicus	Mollusca	Native	+	+	-
Margarites helicinus	Mollusca	Native	+	+	+
Littorina saxatilis	Mollusca	Native	+	+	+
Littorina obtusata	Mollusca	Native	+	+	+
Macoma balthica	Mollusca	Native	+	+	+
Mya truncata	Mollusca	Native	+	+	+
Crassostrea gigas	Mollusca	NIS	+	+	-
Botryllus schlosseri	Tunicate	NIS	+	-	-
Ciona intestinalis	Tunicate	NIS	+	-	+
Styela clava	Tunicate	NIS	+	-	-
Jassa marmorata	Crustacean	NIS	-	-	+
Crepidula fornicata	Mollusc	NIS	+	+	+
Caprella mutica	Crustacean	NIS-high	+	+	+
Caprella mutica	Crustacean	NIS-high	-	-	+
Littorina littorea	Mollusc	NIS-high	+	+	+
Botrylloides violaceus	Tunicate	NIS-high	+	+	-
Carcinus maenas	Crustacean	NIS-high	+	+	+
Mya arenaria	Mollusc	NIS-high	+	+	+
Total			22	17	16

meetings for future use. Example specimens of invasive and similar native species were also brought to workshops and meetings; participants were allowed to handle these and shown how to distinguish them. We found that the new eDNA collection methods were easy for people to learn and there was a general positive reception by trainees. We conclude that eDNA method is a great tool for establishing an ongoing NIS monitoring program in the Canadian Arctic through the development of a community based monitoring (CBM) network/capacity.

DISCUSSION

Common eDNA protocols require the use of a peristaltic pump and freezing samples until lab analysis. The cost of the pump limits sampling at multiple sites simultaneously. Also, storing/shipping frozen samples in remote regions is risky. Thus the new sampling method (syringe filtration) and preservation (buffer instead of freezing) we developed ensures the feasibility of the eDNA method for the Arctic. This new method is also revolutionary in that it limits cross-contamination between samples and its simplicity allows inexperienced collaborators to collect additional eDNA samples. A new efficient, fast and cheap DNA extraction method has also been developed and tested *in vitro*. This important reduction in cost with this new method allowed us to significantly increase the sample size included in the analysis (80 samples were collected per port instead of the expected 30 samples in Churchill and 10 in Iqaluit).

At present, most of benthic metazoans are represented either by the 18S rRNA gene or COI gene. Although these markers have different advantages and offer different taxonomic resolutions, both suffer similar limitations related to incomplete databases and primer specificities, and ideally should be coupled (Cowart et al. 2015). The V4 fragment of the 18S is limited for species-level assignments and provides less accurate diversity estimates than COI (Tang et al. 2012), but is short and easy to PCR amplify and sequence using Illumina technology. The COI marker remains less suitable than the 18S rDNA marker for the design of universal primers (Carugati et al. 2015), and the use of COI is hampered by difficulties in assigning higher taxonomic levels to those sequences that lack close correspondence in the reference database (Deagle et al. 2014). Nevertheless, some key species could only be detected using the 18S marker for which there is no reference COI sequence. Our results indicate that combining multiple COI and 18S primer sets will capture the broadest metazoan Arctic biodiversity.

Integrating Arctic data within the global Coastal SEES Collaborative Research project requires the standardization of similar sampling methods and laboratory processes. This collaboration aims to integrate the Arctic eDNA data and the recent national Canadian Arctic risk assessments for ship-mediated introductions within a global Nonindigenous Species Risk Assessment and Prediction System (NIS-RAPS). This will enable participation in an iterative loop of guidance and information between the research team and national and international policy makers. In July, A. Lacousière and K. Howland presented and participated in a meeting with international collaborators at the University of Notre Dame. This meeting allowed for the development of globally standardized sampling methods and laboratory processes which are being applied to our data collected from the Canadian Arctic. A second meeting will be held on February 1, 2016 to update projects and discuss analyses and sampling in Summer 2016.

Finally, it is necessary to expand the dimension of DNA sequence databases by gathering knowledge on gene copy numbers and polymorphisms. With this new information on intra-genomic variation in hand, it will be possible to refine sequence taxonomic assignments and quantitative ecological inferences. For this purpose, benthic specimens collected in ports are currently being sequenced and will be added to the pipeline of this project.

CONCLUSION

The initial research and training through this study will provide the foundation for establishing an ongoing NIS monitoring program in the Canadian Arctic and will address research priorities and management needs by developing a cost-effective mechanism for regular monitoring at port sites that involves the development of relatively simple standardized sampling approaches and training/engagement at the community level. This information will assist the development of further targeted monitoring programs for invasive species in order to maintain the integrity of coastal marine ecosystems which are critical to the production and survival many invertebrates that are a key link for harvested fish and marine mammal stocks in the Arctic.

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Appendix 1. Potential Arctic invaders (Chan et al. 2012, 2015, Goldsmith 2016) with perfect matches for each primer set. Potential Arctic NIS were classified (higher vs. lower risk) by Goldsmith (2016) according to the number of barriers they have to introduction and establishment and according to documented information in published articles, grey literature and global invasive species lists available on the web.

Taxonomic group	Species	Status	F-574_R-952	TAReuk454FWD1_TAReukREV3	mlCOIintF_jgHCO2198	mlCOIintF_HCO2198	Taxonomic group	Species	Status	F-574_R-952	TAReuk454FWD1_TAReukREV3	mlCOIintF_jgHCO2198	mlCOIintF_HCO2198
Bryozoan	*Membranipora membranacea*	High	1	1	1		Crustacean	*Cercopagis pengoi*	Low	1	1		
Crustacean	*Amphibalanus (Balanus) improvisus*	High			1	1	Crustacean	*Charybdis hellerii*	Low				
Crustacean	*Balanus trigonus*	High		1	1	1	Crustacean	*Dyspanopeus sayi*	Low			1	1
Crustacean	*Caprella mutica*	High			1		Crustacean	*Elminius modestus*	Low		1		
Crustacean	*Carcinus maenas*	High	1	1	1		Crustacean	*Eriocheir sinensis*	Low	1	1	1	1
Crustacean	*Paralithodes camtschaticus*	High	1	1	1		Crustacean	*Gammarus tigrinus*	Low		1		
Crustacean (barnacle)	*Amphibalanus amphitrite*	High		1	1	1	Crustacean	*Hemigrapsus penicillatus*	Low	1	1	1	
Crustacean (barnacle)	*Amphibalanus eburneus*	High		1	1	1	Crustacean	*Hemigrapsus sanguineus*	Low	1	1		
Crustacean (barnacle)	*Amphibalanus reticulatus*	High		1	1	1	Crustacean	*Hemimysis anomala*	Low	1	1		
Crustacean (barnacle)	*Austrominius modestus*	High					Crustacean	*Percnon gibbesi*	Low			1	1
Mollusc	*Littorina littorea*	High	1	1	1		Crustacean	*Pontogammarus robustoides*	Low		1	1	1
Mollusc	*Mya arenaria*	High	1	1	1		Crustacean	*Rhithropanopeus harrisii*	Low			1	1
Tunicate	*Botrylloides violaceus*	High	1	1	1		Crustacean	*Sphaeroma terebrans*	Low				
Algae	*Aglaothamnion halliae*	Low		1	1		Crustacean	*Synidotea laevidorsalis*	Low				
Algae	*Alexandrium catenella*	Low	1	1	1		Crustacean (amphipod)	*Caprella equilibra*	Low		1		
Algae	*Alexandrium minutum*	Low	1	1	1		Crustacean (amphipod)	*Crassicorophium bonelli*	Low				
Algae	*Alexandrium ostenfeldii*	Low	1	1	1		Crustacean (amphipod)	*Jassa marmorata*	Low				
Algae	*Alexandrium peruvianum*	Low					Crustacean (barnacle)	*Conchoderma auritum*	Low		1		
Algae	*Alexandrium taylori*	Low	1	1			Crustacean (barnacle)	*Conchoderma virgatum*	Low		1		
Algae	*Antithamnionella ternifolia*	Low					Crustacean (barnacle)	*Megabalanus coccopoma*	Low		1		
Algae	*Chara connivens*	Low	1	1			Crustacean (barnacle)	*Megabalanus spinosus*	Low		1		
Algae	*Chattonella aff verruculosa*	Low					Crustacean (barnacle)	*Megabalanus tintinnabulum*	Low		1	1	1
Algae	*Cladophora sericea*	Low	1				Crustacean (copepod)	*Centropages typicus*	Low	1	1		
Algae	*Codium fragile ssp tomentosoides*	Low					Crustacean (copepod)	*Heterolaophonte stroemi*	Low				
Algae	*Codium webbiana*	Low					Crustacean (copepod)	*Nitokra lacustris*	Low				
Algae	*Dasya baillouviana*	Low		1			Crustacean (copepod)	*Paronychocamptus huntsmani*	Low				
Algae	*Fucus evanescens*	Low					Crustacean (copepod)	*Schizopera clandestina*	Low				
Algae	*Heterosiphonia japonica*	Low		1			Diatom	*Coscinodiscus wailesii*	Low		1		
Algae	*Hypnea musciformis*	Low		1	1	1	Diatom	*Prorocentrum minimum*	Low	1	1	1	
Algae	*Lophocladia lallemandii*	Low					Echinoderms	*Hydroides elegans*	Low	1	1		
Algae	*Ostreopsis ovata*	Low			1		Fish	*Alepes djedaba*	Low				
Algae	*Polysiphonia morrowii*	Low		1	1	1	Fish	*Neogobius melanostomus*	Low	1	1	1	
Algae	*Sargassum muticum*	Low			1		Mollusc	*Anadara inaequivalvis*	Low				
Algae	*Stypopodium schimperi*	Low					Mollusc	*Brachidontes pharaonis*	Low				
Annelid	*Ficopomatus enigmaticus*	Low	1	1			Mollusc	*Cerithium scabridum*	Low				
Annelid	*Hydroides ezoensis*	Low	1	1			Mollusc	*Corbula gibba*	Low	1	1		
Annelid	*Marenzelleria neglecta*	Low			1	1	Mollusc	*Crassostrea gigas*	Low	1	1	1	1
Annelid	*Marenzelleria viridis*	Low	1	1			Mollusc	*Crepidula fornicata*	Low	1	1		
Annelid	*Mytilicola orientalis*	Low	1	1			Mollusc	*Dreissena polymorpha*	Low	1	1		
Annelid	*Polydora ciliata*	Low	1	1			Mollusc	*Lithoglyphus naticoides*	Low				
Annelid	*Polydora cornuta*	Low			1		Mollusc	*Lyrodus medilobatus*	Low				
Annelid	*Pseudobacciger harengulae*	Low					Mollusc	*Musculista senhousia*	Low	1	1	1	
Annelid	*Pseudopolydora paucibranchiata*	Low	1	1	1		Mollusc	*Mytella charruana*	Low			1	
Annelid	*Spirorbis marioni*	Low					Mollusc	*Mytilopsis leucophaeata*	Low	1	1		
Annelid (Nematode)	*Ascolaimus elongatus*	Low	1	1			Mollusc	*Perna perna*	Low	1	1	1	
Annelid (Nematode)	*Ascolaimus sp.*	Low	1	1			Mollusc	*Perna viridis*	Low	1	1	1	
Annelid (Nematode)	*Axonolaimidae*	Low					Mollusc	*Rapana venosa*	Low	1	1	1	1
Annelid (Nematode)	*Daptonema tenuispiculum*	Low					Mollusc	*Strombus persicus*	Low			1	1
Annelid (Nematode)	*Geomonhystera sp.*	Low	1	1			Mollusc	*Teredo bartschi*	Low				
Annelid (Nematode)	*Prochromadora orleji*	Low					Mollusc	*Theora lubrica*	Low				
Ascidian	*Didemnum cf. lahillei*	Low					Mollusc	*Xenostrobus securis*	Low	1	1		
Ascidian	*Didemnum vexillum*	Low		1	1		Plant	*Acrothamnion preissii*	Low				
Bryozoan	*Tricellaria inopinata*	Low					Plant	*Asparagopsis armata*	Low		1	1	1
Bryozoan	*Victorella pavida*	Low					Plant	*Caulerpa racemosa var. cylindracea*	Low	1			
Cnidarian	*Cordylophora caspia*	Low	1	1			Plant	*Caulerpa taxifolia*	Low	1			
Cnidarian	*Drymonema dalmatinum*	Low	1	1			Plant	*Spartina anglica*	Low				
Cnidarian	*Garveia Franciscana*	Low					Plant	*Undaria pinnatifida*	Low	1	1	1	
Cnidarian	*Maeotias marginata*	Low	1	1			Tunicate	*Botryllus schlosseri*	Low	1	1	1	1
Cnidarian	*Moerisia lyonsi*	Low					Tunicate	*Ciona intestinalis*	Low	1	1		
Cnidarian	*Phyllorhiza punctata*	Low	1	1	1	1	Tunicate	*Mogula manhattensis*	Low				
Cnidarian	*Rhopilema nomadica*	Low	1	1	1		Tunicate	*Polyandrocarpa zorritensis*	Low	1	1		
Crustacean	*Acartia tonsa*	Low	1	1	1	1	Tunicate	*Styela clava*	Low	1	1		


AMUNDSEN

Automated Ice and Oil Spill Mapping – Protecting Arctic Coastal Regions and Communities

Project Leader

David Clausi (University of Waterloo)

Network Investigators

Michael Collins (University of Calgary)
Christian Haas (York University)
Andrea Scott (University of Waterloo)
Alexander Wong (University of Waterloo)

Collaborators

Chris Hill (Canatec)
Bill Jeffries (LookNorth)

HQP

Fan Li, Doctoral Student (University of Waterloo)
Javad Shafiee, Doctoral Student (University of Waterloo)
Lei Wang, Doctoral Student (University of Waterloo)
Ross Duquette, Honours Undergraduate Student (University of Waterloo)
Meng Ma, Masters Student (University of Calgary)
Dennis Sherman, Masters Student (York University)
Catherine Tsouvaltsidis, Masters Student (York University)
Linlin Xu, Post-Doctoral Fellow (University of Waterloo)
Reza Mani, Research Associate (York University)
Dmitriy Danchenko, Undergraduate Student (York University)

ABSTRACT

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

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

KEY MESSAGES

- This project seeks to develop a next-generation satellite-based ice and oil-slick surveillance, detection, and identification system so that Canadians receive early warning of marine hazards. Canadians will benefit since measures can then be taken to reduce the impact of these hazards on navigation and local communities. The key collaborator is the Canadian Ice Service (CIS).
- Automated ice interpretation in synthetic aperture radar (SAR) is important for rapid and accurate ice map generation to support navigation and environmental modelling.
- There is no known system that reliably detects oil spills in oceans. That the Arctic regions will have an increase in ship traffic over the coming decades is expected and this will increase the risk of oil spills in waterways that can affect local communities and ecosystems.
- Remote sensing provides the only feasible means to identify oil spills over vast ocean regions. Oil spill recognition from remotely sensed imagery is challenging. Our research group is developing novel means to identify oil spill candidates in SAR imagery. Additional ground truth data for this research will be provided via the CIS's ISTOP (Integrated Satellite Tracking of Pollution) system.
- New sea ice data sets for analysis that include quad pol data that can be converted to compact polarimetry (CP) have been acquired via CIS.
- A protocol is being developed to evaluate the existing MAGIC sea ice classification system across different seasons and locations, necessary for operational considerations.
- A new initiative with Dr. Derek Mueller (Carleton) to evaluate MAGIC algorithms to perform identification of ice islands has been started.

- An airborne ice thickness and roughness observation campaign as performed in April 2015 and acquired extensive data coincident with SAR imagery to facilitate algorithm development and validation.
- There was a setback in graduate student recruitment since a student who was expected to start in September 2015 at the University of Waterloo declined. A delay in hiring a student to work at the University of Calgary occurred due to an overseas sabbatical.

OBJECTIVES

We continue to follow the objectives that were indicated as part of our original project proposal accepted by ArcticNet on April 1, 2015. Our objectives include:

1. Conducting research into algorithms to automatically create state-of-the-art simulated SAR images containing ice and oil slicks since natural such scenes are not known;
2. Investigating 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. Creating tools and appling these tools to dual-pol SAR imagery to generate our own in-house ground truth scenes that illustrate basic ice types (multi-year, first year, new) and open water;
4. Developing and evaluating automated algorithms to segment fine quad-pol, and compact polarimetry (CP) SAR images and classify ice and water regions at available resolution;
5. Developing and evaluating automated algorithms to accurately identify basic categories of ice (multi-year, first year, new) and open water, using SAR dual-pol, fine quad-pol, and CP imagery without user intervention;
6. Developing automated oil spill detection algorithms using SAR dual pol, fine quad pol, CP imagery with true positive accuracy of over 90% and false negative accuracy of 80%;
7. Developing techniques to use ice classification outputs as inputs into data assimilation models to improve estimates of ice concentrations and thickness over large regions;
8. Generating ice concentration maps from SAR imagery based on deep learning techniques using convolutional neural networks;
9. Assessing the ability of MAGIC algorithms to demarcate and classify ice islands in SAR imagery (in collaboration with Dr. Derek Mueller, Carleton University);
10. Developing methodologies to transfer algorithms to other scientists with a need to map ice and oil slicks and to CIS for consideration to be used operationally, and to transfer image output maps to the Inuit for evaluation on transportation and safety in ice regimes;
11. Continuing long-term observations of sea ice conditions and thickness of hazardous ice features in the Beaufort Sea, extending from the 2009 Beaufort Regional Environmental Assessment;
12. Obtaining airborne validation data coincident with SAR image acquisitions and to retrieve quantitative information about ice morphology (roughness and ridging) and thickness from those measurements to act as ground validation; and
13. Training HQP in the development of advanced computer vision algorithms, the understanding of Arctic needs and role in Canada, and to build understanding of the impact of global warming and its monitoring.

INTRODUCTION

Preamble. Satellite imagery is the only feasible means for monitoring the remote and vast Arctic. Synthetic aperture radar (SAR) sensors flown on satellites provide a key data source for Arctic monitoring since SAR is an active sensor capable of capturing consistent scenes day or night in all-weather conditions. The Canadian Ice Service (CIS) manually interprets, amazingly, 12000 SAR images each year and this is expected to increase with increased Arctic shipping traffic and increased availability of SAR imagery due to the multi-satellite RADARSAT Constellation Mission (RCM) planned for deployment in 2018. RCM satellites carry an advanced SAR called 'compact polarimetry' (CP) expected to improve ice and oil monitoring (Charbonneau et al., 2014). Increasing ship activity in the Arctic due to the receding and thinning ice conditions demonstrates a critical reason to monitor ice conditions and oil spills to protect Arctic coastlines and to effectively serve remote communities.

Why monitor Arctic sea ice? 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. Thick ice is an obstacle and a sinking hazard to marine vessels. Ships need timely ice information to plan safe routes. Such knowledge of thin ice and leads can assist route determination for shipping and ice breaker support. Fast ice along coastal regions should be identified to minimize risk for ships moving through these conditions. 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).

Why monitor Arctic oil spills? 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 (Pavlakis et al., 1996). The negative impact of oil spills on Arctic coastal regions may become significant with the expected increased ship traffic in these regions (Grabowski et al., 2014), including the corresponding impacts on seabirds, aquatic animals, and coastal ecosystems along shorelines in proximity to Arctic communities. There is no doubt that intentional spills must be quickly identified and associated with particular ships to support legal proceedings against the offenders and act as a deterrent. Automated monitoring is an essential part of identifying oil spills given the vastness of the Arctic.

What are the challenges for automated monitoring? Since its inception, SAR has been used to monitor sea ice; however, developing computer algorithms that can correctly identify ice types and oil slicks in SAR imagery has been elusive. Incidence angle backscatter variations, high within-class class backscatter variability, masking effects of melting snow on ice, and wind variations are key challenges that thwart automated algorithms for such monitoring. Good success has been recently achieved by Prof. Clausi's research group by developing an algorithm within their MAGIC software system (Clausi et al., 2010) that uses an automated approach to identify ice versus open water for data captured across all seasons in one Arctic location (Leigh et al., 2014). SAR is well suited to scene capture 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). A novel challenge is the ability to automatically identify oil spills in ice-infested waters near coastal regions since, for example, land can mask wind effects causing dampening of the ocean and this produces signatures that can be mistaken for oil spills. "Although a significant body of knowledge exists to describe the use of remote sensing technologies for oil spill detection and monitoring on open water, there is little research available to describe their performance in ice-affected marine environments. Dedicated research is therefore required to fully assess the utility of remote sensing technologies under Arctic conditions (Warren et al., 2013).”

Advances. MAGIC uses an advanced unsupervised classification algorithm demonstrated to reliably segment a SAR scene into visibly distinct segments (Yu and Clausi, 2007, 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., 2014). The ice/water classification example in Figure 1 shows water in the HH pol with bright backscatter that can easily be confused with the ice on the right hand side. The HV-pol scene minimizes incidence angle variations, especially over water, and is necessary for algorithmic success. The RCM will provide operational compact polarimetry (CP) scenes and this is expected to provide improved data for ice/water mapping, ice typing, and oil spill identification. Use of simulated CP data prior to RCM launch is a necessary research direction in support of future operational CP scences. Investigation of methods for identifying oil spills in ice-infested waters in coastal regions is a novel research topic. No refereed publications are known that address this issue, however, this is a critical problem to resolve with increased shipping and oil spill threats to the extensive Arctic coastlines.

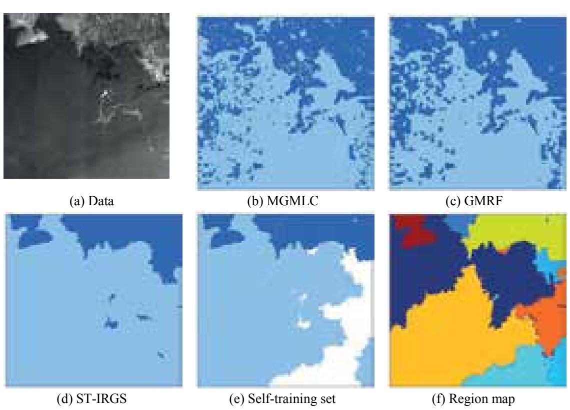

Figure 1. Classification results of the data captured on October 3, 2010. (a) shows the HV polarization of the data, with original training samples overlain on the image (red: ice; blue: open water). (b), (c), and (d) are classification results of MGMLC, GMRF, and STIRGS respectively. (e) is the final training sample map expanded by self-training of STIRGS. (f) is the final region map of STIRGS.WW.

ACTIVITIES

(project source indicated in [ ] brackets)

1 - Improving MAGIC Software for Operational Use [ArcticNet]

- We started preparing software requirements in communication with CIS personnel to allow MAGIC to input and output standard georeferenced data that can be used by data processing systems at CIS.
- We provided means in MAGIC to adjust output colours on classification results.
- Plans are being put in place to input quad pol data and compact polarimetry (CP) data and to be able to generate dedicated features based on CP data (Dabboor and Geldsetzer, 2014).

2- SAR Sea Ice Imagery Acquisition and Planning [ArcticNet]

- Previously we produced pixel-level ice/water ground truth of 63 full SAR scenes (10 km x 10 km) in the Beaufort Sea validated by an ice analyst. We are investigating production of ground truth using the same data by breaking up the ice into constitutive categories, namely, multi-year, first year, and new ice.
- Quad-pol data that was used to assess ice classification ability of CP data (Dabboor and Geldsetzer, 2014) was provided to the UW group by CIS. This data will support testing in MAGIC for importing quad-pol scenes, converting quad pol scenes to CP data, and generating features based on CP data.

- WWSAR data of ice islands has been provided by Dr. Derek Mueller (Carleton) to evaluate the ability of MAGIC algorithms to demarcate and classify ice islands. We are considering the potential for co-supervising a graduate student who would work specifically on this research topic.
- Field studies have provided field captured ground truth coincident with RADARSAT-2 scenes.
- We generated scenes with true labels for testing: we need to augment the Beaufort scenes by breaking up the generic ice category into multi-year, first year, and new ice types. We can implement a classification algorithm either by finding three classes directly or identifying multi-year, first year and new ice from using the existing algorithm (SVM-IRGS) ice/water results.

3 - SAR Oil Spill Imagery Description [ArcticNet]

- From CIS, we have acquired 180 oil spill SAR scenes from the ISTOP (Integrated Satellite Tracking of Pollution) (https://www.ec.gc.ca/glaces-ice/default.asp?lang=En&n=40897129-1) 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 in the year of 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.

4 - Testing and Evaluation [ArcticNet]

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

5 - Oil Spill Characterization [ArcticNet]

- An algorithm that is able to perform sensitive dark spot detection for SAR scenes of oceans has been developed (Xu et al., 2015a,b). The algorithm is designed to thoroughly identify any candidate oil spills in a SAR scene.
- Research into classifying the dark spots into either oil spills or other phenomena has started.

6 - Simulation of SAR Imagery [ArcticNet]

- A methodology for simulating polarimetric C-band backscattering has been started.
- GRECOSAR software is being used to simulate backscatter from a simple smooth disc-shaped sea ice floe.

- Challenges have been encountered enabling the software to properly simulate backscatter from the sea surface.
- Dialogues with the developer of the software based on small experiments are ongoing.

7 - Ice Concentration Estimation Using CNNs [MEOPAR and ArcticNet]

- An accurate estimate of ice concentration at a high spatial resolution (on the order of 1 km) is important for assessing the development of an oil spill and its impact on the marine environment.
- We have designed a deep learning-based convolutional neural network (CNN) that is able to refine ice concentration estimates provided by operational ice charts into detailed pixel-by-pixel ice concentration estimates.

8 - Field Work Activities [MEOPAR and ArcticNet]

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

9 - Relationships with Other Research Groups [ArcticNet and MEOPAR]

- A new project with the goal of automatically demarcating ice islands in high resolution SAR imagery has been initiated with Derek Mueller (Carleton).
- Discussions with Trevor Bell (SmartICE) with Trevor Bell have been initiated with an interest for using MAGIC-generated maps for local ice support information.
- MEOPAR surveys were conducted with operational funding support from the MEOPAR project, where data were used for ice hazard assessment and assimilation. The surface roughness data also support a project on observation on melt ponding and ice decay based on PolSAR imagery.

10 - Personnel [ArcticNet]

- A PhD student was supposed to arrive at the University of Waterloo to work on automated ice interpretation. However, in July 2015, this student indicated that due to immigration reasons, his wife would not be able to stay in Canada so the candidate decided to return to his home country.
- A co-op student (Ross Duquette) was hired to work in the winter term (Jan/16-Apr/16) at the University of Waterloo to improve the MAGIC software system.
- A post-doctoral fellow (Linlin Xu) is responsible for algorithmic design, implementation, and testing of the SAR ice and oil classification algorithms.
- A graduate research assistant (Catherine Tsourvaltsidis) and research associate (Rez Mani) developed and integrated the camera and laser scanning system in order to derive two-dimensional information of surface roughness and ridging, which ultimately will be more closely related to SAR backscatter than just ice thickness.
- A summer student (Dmitriy Danchenko) and MSc. student (Dennis Sherman) processed the laser scanning data to retrieve surface elevation models.

RESULTS

1. Semi-supervised Approaches for Scene Classification [ArcticNet]

We have prepared and published a number of papers on techniques that involve minimal operator interaction in order to perform full scene classification (Li et al., 2015a-e). These techniques involve the operator selecting a limited number of samples (~10) per class from a particular scene and then automatically classifying each pixel in the scene to these classes. Although originally designed for hyperspectral imaging, we have started to investigate the potential of these semi-supervised approaches to help generate pixel-based ground truth and to assist operational activities at CIS.

2. Oil Spill Detection – Dark Spot Detection [ArcticNet]

We have made strong progress developing a technique to detect dark spots in SAR ocean imagery (Figure 2) with the intent to identify all the potential oil spill candidates (Xu, et al. 2015a,b). The conditional random field approach is novel compared to the basic thresholding approaches currently found in the research literature.

3. Weakly Supervised Approach for Operational SAR Sea Ice Classification [ArcticNet]

We have developed a weakly supervised approach for classification of SAR images that have accompanying ice analysis charts. Polygons in the ice analysis represent regions of consistent ice. Ice data for each polygon is stored as an "egg code" that records the ice types found in that particular polygon region. We use only this label information provided by the egg code as input to an

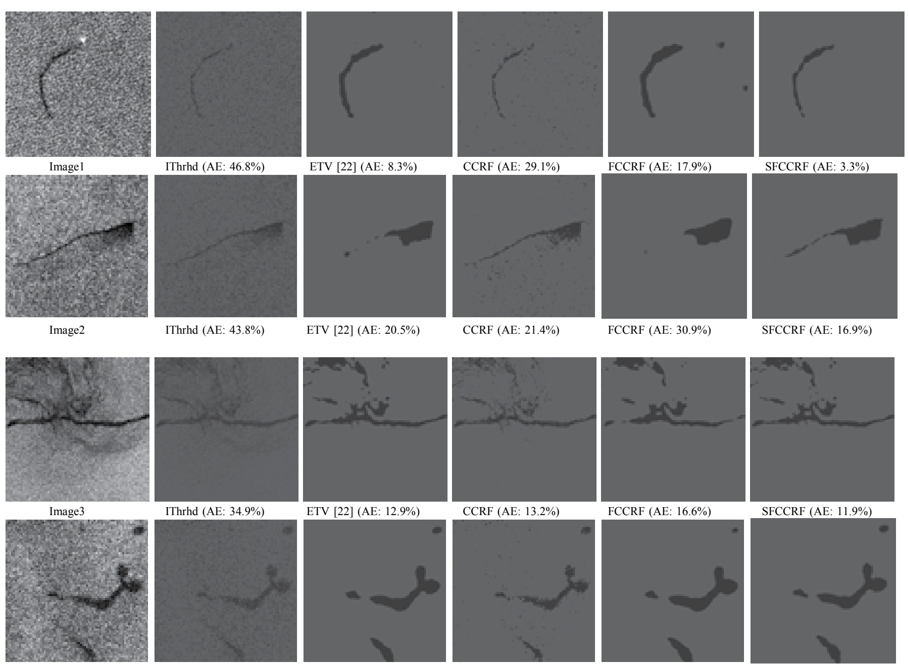

Figure 2. Detecttion of oil spill candidates by five different methods on four images. Comparing with other methods, the proposed SFCCRF method is less affected by the background and target heterogeneities, and in the meantime can more accurately identify the boundaries and the linear targets.

automated procedure that can then classify each pixel in the full scene. We have nearly completed writing a paper on this topic to be submitted to *IEEE Geoscience and Remote Sensing*.

4. Despeckling of Complex SAR Imagery [ArcticNet]

In anticipation of dealing with complex and eventually CP SAR imagery, we have developed a new technique for despeckling of complex SAR data. This will act as a stepping stone to eventually develop methods to despeckle source CP SAR imagery.

5. Post-Field Work Data Processing [ArcticNet]

Based on data captured during the airborne field campaign performed in April 2015 it was found that the larger-than-average multiyear ice thickness in April 2015 led to the survival of a unique ice band in the Beaufort Sea well into August, showing the importance of initial ice conditions for seasonal predictions of summer sea ice.

6. Ice Concentration Estimation Using Deep Convolutional Neural Networks (CNNs) [ArcticNet and MEOPAR]

A new approach for estimating ice concentration from dual-pol RADARSAT-2 imagery during the melt season has been created and tested using CNNs (Wang et al., 2015). 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. The CNN algorithm has been applied to the estimation of ice concentration in the Beaufort Sea (Wang et al., 2015) and the Gulf of St. Lawrence with promising results. Smaller scale details (e.g., floes and ice eddies) seen in the SAR imagery are well represented in the estimated ice concentration.

DISCUSSION

Advanced Methods for SAR Sea Ice Classification. The Canadian Ice Service (CIS) has an active interest in being able to automatically identify sea ice in SAR imagery. Ice maps produced by the CIS can be used to infer ice thickness and ice strength to facilitate decision support systems for shipping and icebreaking. The existing approach within the MAGIC system (Leigh et al., 2014) is used for binary pixel-level classification of ice and open water. In support of CIS operations and an interest in being able to provide ice maps more readily to those who live and work in the Arctic, we wish to further assess 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), and across different time periods (to evaluate performance especially in the more complicated freeze-up and melt periods). Algorithm parameters may be sufficiently generic to perform satisfactorily over ice types, regions, and time periods or dedicated parameters may have to be developed.

Advanced Methods for SAR Oil Spill Detection. CIS operates a manually operated system (ISTOP) designed to identify ocean-based oil slicks. To save time and money and to reduce human bias, there is a demand for machine algorithms that can analyze SAR imagery for oil spill detection. Even the ability to flag all potential dark spot candidates is important given the vastness of the oceans and the high volume of data expected with the RCM. This means that detected oil slick candidates would require an operator to determine if they are oil slicks, but the algorithm would save time because the candidates would be automatically provided. Oil slicks have look-alikes due to the sensor characteristics, natural films, and low wind speeeds. However, we are expecting that CP data will enhance the detection of oil spills (Li et al., 2014; Yin et al., 2015).

Inuit Traditional Knowledge. SmartICE (Sea-Ice Monitoring and Real-Time Information for Coastal

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

CONCLUSION

To effectively address the problem of improving the mapping of oil spills and ice in Arctic regions, we are conducting research in a number of ways. Field work is performed in the ice-infested regions to generate ground truth that validates the ice types and properties. Further ground truth is enabled using ice analysts assessment of operational SAR imagery. Coincident satellite imagery is then used to correlate radar measurements with these ice types. Automated tools can then be developed and refined to identify ice, ice types, open water, and oil slicks. The new Canadian radar-based satellites, known as the RADARSAT Constellation Mission (RCM), are planned for launch in 2018 and algorithms dedicated to the new imaging modes on this series of satellites will be addressed as part of this project.

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

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ArcticNet Long-Term Oceanic Observatories: Continuation and Synthesis of the Existing Decadal Records of Physical and Biogeochemical Signals

Project Leader

Dany Dumont (Université du Québec à Rimouski)

Network Investigators

Louis Fortier (Université Laval)
Jean-Eric Tremblay (Université Laval)

Collaborators

Marcel Babin (Université Laval)
Cédric Chavanne (Institut des sciences de la mer de Rimouski, UQAR)
Seth Danielson (University of Alaska Fairbanks)
Alexandre Forest (Université Laval)
Jacqueline Grebmeier (University of Maryland Centre for Environmental Science)
Catherine Lalande (Université Laval)
Guillaume Massé (University of Plymouth)
Eva-Maria Nöthig (Alfred-Wegener Institute Helmholtz Centre for Polar and Marine Research)
Makoto Sampei (Université Laval)
Yvan Simard (Université du Québec à Rimouski)

HQP

Aboyo Essi Enyonam, Doctoral Student (Institut des sciences de la mer de Rimouski, UQAR)
Thibaud Dezutter, Masters Student (Université Laval)
Marie Parenteau, Research Associate (Université du Québec à Rimouski)

ABSTRACT

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

KEY MESSAGES

- Variations in the zooplankton community (swimmers) collected in sediment traps at a single station from 2003 to 2015 in the Beaufort Sea may reflect variations in the dominant current direction (shelf/basin).
- The timing of the ice algae release/phytoplankton bloom in the Canadian Beaufort Sea is not directly linked to ice melt but rather to snow melt.
- Under-ice export fluxes of biogenic matter increase following snowmelt periods in Baffin Bay, likely due to the release of ice algae.
- Annual dinoflagellate cyst fluxes obtained at two sites in the seasonally ice-covered Hudson Bay indicate that trophic status is not the main factor influencing cyst production, as autotrophic and heterotrophic dinoflagellate cysts are equally recorded at the time of the ice breakup and in open water conditions.
- Downward particle flux in the Beaufort Sea highlights the role of the zooplankton community in the transformation of carbon issued from primary production and the transition of that carbon from the productive surface zone to the Arctic Ocean's interior. Sinking carbon flux in late summer is primarily the result of a heterotrophic-driven ecosystem.
- The occurrence of noise transients in the Beaufort Sea corresponded to large-scale ice motion and deformation rates forced by meteorological events, often leading to opening of large-scale leads in the ice cover.
- Thermohaline convection and storm winds act as the main mechanisms underlying resuspension and transport processes in the Canadian Beaufort Sea during winter.
- Wind-driven sea level fluctuations may impact sea-ice cover in winter at the Canadian Beaufort Sea continental slope.

- Upwelling of Atlantic Water along the Canadian Beaufort Sea continental slope is correlated with along-slope northeast winds during both ice-free and ice-covered conditions, although the wind impact is more efficient during open water conditions.

OBJECTIVES

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

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

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

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

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

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

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

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

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

INTRODUCTION

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

In their 1989 paper, Robert H. Bourke, Victor Addison and Robert Paquette, all from the Naval Postgraduate School, reported results obtained from the second scientific expedition that monitored Nares Strait in its entirety in order to characterize pathways of

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

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

ACTIVITIES

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

- Five moorings (including seven sediment traps) were recovered and six moorings (including eight sediment traps and two hydrophones) were redeployed jointly by ArcticNet-LTOO and the iBO initiative in the Beaufort Sea on board the CCGS *Amundsen* and *Laurier* in summer 2015. Shawn Meredyk (mooring engineer) coordinated the recovery, calibration and redeployment of moored instruments on board the CCGS *Amundsen* while colleagues at DFO were on charge on board the CCGS *Laurier*.
- Ice-anchored sequential sediment traps were deployed as a LTOO contribution to the Green Edge project at the Green Edge ice camp from April to June 2015. All sediment trap samples were analyzed for measurements of chlorophyll *a*, swimmer identification, particulate organic carbon, total particulate matter, zooplankton fecal pellets, and phytoplankton cell export fluxes. Gabrielle Nadaï, a biology undergraduate student who was awarded an Undergraduate Student Research Award by the Natural Sciences

and Engineering Research Council of Canada, has done the majority of these analyses during summer 2015.

- Two ArcticNet-LTOO moorings carrying McLane mooring profilers (MMPs) that were deployed in 2014 in Fram Strait were recovered in July 2015 by collaborators of the Deep-Sea Ecology and Technology working group of the AWI during their annual expedition to the HAUSGARTEN observatory on board RV Polarstern. Evaluation of the data collected by the MMPs is ongoing.
- In August 2015, a sequential sediment trap was added on the Chukchi Ecosystem Mooring deployed on the northern Chukchi shelf for a 1-year period.
- An oceanographic mooring carrying a sediment trap was deployed in July 2015 as part of the Queen Maud Gulf-Victoria Strait marine ecosystem pilot study.

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

- Analyses on sediment trap samples from the seven traps recovered in the Beaufort Sea in 2015 started in December at Université Laval and are ongoing (splitting + removal and identification of swimmers before measurements of weight, carbon and nitrogen). Microscopic identification of the phytoplankton cells collected in 2014-2015 is also ongoing.
- Microscopic identifications of the phytoplankton cells collected in sediment trap samples from 2003-2014 are also being conducted as part of the long-term monitoring of the pelagic ecosystem function in the Beaufort Sea.
- A research assistant (Marie Parenteau) was hired in May 2015 to do microscopic identifications of phytoplankton cells on sediment trap samples at Université Laval. Marie traveled to the Alfred-Wegener Institute in Germany in November 2015 for a 2-week internship with Dr. Eva-Maria Nöthig, a phytoplankton expert.
- A M.Sc. student (Thibaud Dezutter) started his M.Sc. thesis on swimmers in sediment traps under the supervision of Dr. Louis Fortier within the framework of the LTOO project in 2014-2015 and performed swimmer identification on samples collected over six years at a single station from 2003 to 2015 in 2015-2016.
- Dinoflagellate cyst analyses are conducted on sediment trap samples collected from 2003 to 2015 in collaboration with Dr. Vera Pospelova at the University of Victoria. 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 sea-ice cover, sea surface temperature, salinity, and freshwater input. 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.

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

- A PhD Student, Essi Enyonam Aboyo, has been recruited under the supervision of Dr. Dany Dumont at the Université du Québec à Rimouski and has started familiarization with the MITgcm numerical model used in the project.

RESULTS

The following section includes results obtained in the first year of ArcticNet's phase 4 (2015-2016) as well as results obtained during the previous phases of the Long-Term Oceanic Observatories project that are published or in the process of being published.

Physical forcings and intense shelf–slope fluxes of particulate matter in the halocline waters of the Canadian Beaufort Sea during winter (Forest, Osborne, Fortier, Sampei, and Lowings)

Resolving the mechanisms that support the transfer of particulate matter across the shelf–slope interface is a key issue for the sustainable development of marine resources along continental margins. A better comprehension of shelf–slope exchanges is particularly needed in the Arctic Ocean given the intensification of human activities and rapid environmental changes in this region. Here, we use three years of physical and biogeochemical data collected with taut line moorings deployed from September 2009 to August 2012 over the slope of the Mackenzie Shelf to identify the processes that drive the lateral transport of particulate matter off the shelf. The main dataset consists of particle flux time-series collected with automated sediments traps deployed on moorings at ~80 and ~180 m depth over the mid-slope. We detected a strong vertical discrepancy in the magnitude of particulate mass fluxes that were 20–600% higher at ~180 m than at ~80 m, and up to ~1500% greater during the winter season alone. The high fluxes at ~180 m depth were linked to several sedimentation events occurring from November to May each year, which were not captured by the upper ~80 m traps. These differences corroborate previous studies that documented active transport of resuspended material near the bottom across the shelf-break and in the mid-water column over the slope. Consideration of particle fluxes along with synchronous current time-series, water column properties and meteorological data revealed that thermohaline convection and storm winds act as the main mechanisms underlying resuspension and transport processes. Their combination drives mesoscale eddy formation, downwelling flows and current surges that are characterized by moderate to high velocities (~20–80 cm s^{-1}) sufficient to mobilize sediments. Turbidity near the shelf-break and particle fluxes over the slope were particularly enhanced in winter 2011 (mass fluxes up to ~2 g $m^{-2}d^{-1}$) when a persistent downwelling-favorable wind regime and a large production of winter water were observed. Overall, the amount of winter water events correlated significantly (R^2=0.76) with the magnitude of mass fluxes collected at ~180 m. Our analysis revealed a complex pattern of mean currents over the slope facilitating instabilities, frontal structures, shear and eddying motion. Additional work is needed on erosion mechanisms in the bottom boundary layer and their relationship to regional and mesoscale circulation and eddy activity over the upper slope.

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

The shelfbreak current over the Beaufort Sea continental slope is known to be one of the most energetic features of the Beaufort Sea hydrography. In January 2005, three oceanographic moorings deployed over the Canadian (eastern) Beaufort Sea continental slope simultaneously recorded two consecutive shelfbreak current events with along-slope eastward bottom-intensified flow up to 120 cm s^{-1}. Both events were generated by the local wind forcing associated with two Pacific-born cyclones passing north of the Beaufort Sea continental slope towards the Canadian Archipelago. Over the mooring array the associated westerly wind exceeded 15-20 m s^{-1}. These two cyclones generated storm surges along the Beaufort Sea coast with sea surface height (SSH) rising up to 1.4 m following the two westerly wind maxima. We suggest that the westerly along-slope wind generated a surface Ekman on-shore transport. The associated SSH increase over the shelf produced a cross-slope pressure gradient that drove an along-slope eastward geostrophic current, in the same direction as the wind. This wind-driven barotropic flow was superimposed on the background baroclinic bottom-intensified shelfbreak current that consequently amplified. Summer-fall satellite altimetry data for 1992-2013 show that the SSH gradient in the southeastern Beaufort Sea is enhanced over the upper continental slope in response to frequent storm surge events. Because the local wind forcing and/or sea-ice drift could not explain the reduction of sea-ice concentration over the Beaufort Sea continental slope in January 2005, we speculate that wind-driven sea level fluctuations may impact the sea-ice cover in winter.

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

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

Wintertime water dynamics and moonlight disruption of the acoustic backscatter diurnal signal in an ice-covered Northeast Greenland fjord (Petrusevich, Dmitrenko, Kirillov, Rysgaard, Falk-Petersen, Barber, Boone, and Ehn)

Six and a half month-long records from three ice-tethered Acoustic Doppler Current Profilers deployed in October 2013 in Young Sound fjord in Northeast Greenland are used to analyze the acoustic backscatter signal. The acoustic data reveals a systematic diel vertical migration (DVM) of scattering materials below the land-fast ice during polar night. These materials were likely comprised of zooplankton. The acoustic signal pattern typical to DVM persisted in Young Sound throughout the entire winter including the period of civil polar night. However, polynya-enhanced estuarine-like cell circulation that occurred during winter disrupted the DVM signal favoring zooplankton to occupy the near-surface water layer. This suggests that zooplankton avoided spending additional energy crossing the interface, with a relatively strong velocity gradient, comprised by fjord inflow in the intermediate layer and outflow in the subsurface layer. Instead the zooplankton tended to favor remaining in the upper 40 m layer where also the relatively warmer water temperatures associated with upward heat flux during enhanced estuarine-like circulation could be energetically favorable. Furthermore, our data show moonlight disruption of DVM in the subsurface layer and weaker intensity of vertical migration beneath snow covered land-fast ice during polar night. Using existing models for lunar illuminance and light transmission through sea ice and snow cover, we estimated under ice illuminance and compared it with known light sensitivity for Arctic zooplankton species.

First oceanographic observations on the Wandel Sea shelf in Northeast Greenland: Tracing the Arctic Ocean outflow through the western Fram Strait and the glacier-ocean interaction during winter (Dmitrenko, Kirillov, Rudels, Babb, Toudal Pedersen, Rysgaard, Kristoffersen, and Barber)

The first-ever conductivity-temperature-depth (CTD) observations on the Wandel Sea shelf in North Eastern Greenland were collected in April-May 2015. They were complemented by CTDs taken along the continental slope during the Norwegian FRAM 2014-15 drift. The CTD profiles are used to reveal the origin of water masses and interactions with ambient water from the continental slope and the tidewater glacier outlet. The subsurface freshened water is associated with the Pacific Water outflow from the Arctic Ocean. The underlying Halocline separates the Pacific Water from a deeper layer of Polar Water that has interacted with the warm Atlantic water outflow through Fram Strait recorded below 140 m. Over the outer shelf, the Halocline shows numerous cold density-compensated intrusions indicating lateral interaction with an ambient Polar Water mass across the continental slope. At the base of the Halocline, colder and turbid water intrusions were observed at the front of the tidewater glacier outlet. On the temperature-salinity plots these profiles present a mixing line that is different from the ambient water and seems to be conditioned by the ocean-glacier interaction. Our observations of Pacific Water are set within the context of upstream observations in the Beaufort Sea and downstream observations from the Northeast Water Polynya, and clearly show the modification of Pacific water during its advection across the Arctic Ocean. Moreover, ambient water over the Wandel Sea Slope shows different thermohaline structures indicating the different origin and pathways of the on-shore and offshore branches of the Arctic Ocean outflow through Fram Strait.

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

Sequential sediment traps were deployed at 25 and 100 m under-ice from April 15 to June 9 2015 during the Green Edge ice camp in Baffin Bay to measure the particulate material being exported from the ice. Measurements of total particulate matter (TPM), chlorophyll *a* (Chl *a*), particulate organic carbon (POC), phytoplankton cells, swimmers, and zooplankton fecal pellets have been performed on the trap samples. Although the release of ice algae has occurred after the sampling period (June 12-15), interesting patterns emerged from the data collected. An increase in all parameters measured and in fecal pellet width was observed at 25 m at the end of May. Whereas TPM fluxes and FPC fluxes also increased at 100 m during the same period, Chl *a* fluxes and fecal pellet width at that depth remained similar than in April and early May. Chl *a* fluxes, FPC fluxes, and fecal pellet widths were higher at 100 m than at 25 m in April and most of May, but were similar at both depths from the end of May to the end of the deployment in June. These results, along with the observation of larger copepods collected in the 25 m-trap at the end of May and in June only, indicate that large copepods contributing to most of the zooplankton biomass and FPC fluxes migrated towards the surface at the end of May when primary production in the upper waters increased, as reflected by enhanced Chl *a* fluxes. Similarly wide fecal pellets at 25 m and 100 m at the end of May and in June also support the migration of larger copepods from deeper waters towards the surface. However, while the composition of the export fluxes varied differently at 25 and 100 m, the magnitude of the TPM exported at both depths was similar from April to June. Overall, these results indicate that, although export fluxes were low, a temporal change in the composition of the export fluxes was observed under > 1 m of ice and > 15 cm of snow during the complete sampling period. However, export fluxes appeared to increase following snowmelt periods, which likely triggered the release of ice algae (Fortier et al., 2002).

Swimmers in sediment traps: changes (or lack thereof) in zooplankton community at a single station from 2003 to 2015 (Beaufort Sea shelf break, Canadian Arctic) (Dezutter, Lalande, and Fortier)

Moored sediment traps were deployed to monitor the downward flux of organic and inorganic matter at the Beaufort Sea shelf break over six years between 2003 and 2015. Because ship-based observations of zooplankton communities in the Arctic Ocean are usually limited to the season of minimum ice extent (July-October), swimmers, zooplankton actively swimming into the traps, are used as indices of seasonal and interannual fluctuations in zooplankton community. Preliminary results for swimmers collected at the BR-G mooring in 2011-2012 and 2012-2013 showed a similar taxonomic composition for both years. The carnivorous *Paraeucheta glacialis* and the omnivorous *Metridia longa* dominated the copepod assemblage both years, while the herbivorous *Calanus glacialis* and *Calanus hyperboreus* were less abundant in 2012-2013 (2% and 4%) than in 2011-2012 (8% and 7%). The migration of herbivorous copepods is apparent and correlated to the amount of daylight. Lower herbivorous abundance in summer 2013 may be due to the late ice breakup and lower primary production (also reflected in lower summer POC flux. The carnivorous *P. glacialis* feeds on *Calanus* copepods and therefore displayed a similar seasonal vertical migration pattern. Higher abundance of the omnivorous *M. longa* in winter 2013 may be explained by a higher POC flux at that time, and Pacific expatriate copepods were collected in summer of both years.

Seasonal and interannual variability in the release of ice algae and phytoplankton bloom in the Beaufort Sea (Lalande, Parenteau, and Fortier)

Microscopic observations of phytoplankton cells collected in sediment traps at the Beaufort Sea shelf break in 2005-2006, 2012-2013, and 2014-2015 indicate a peak in exported phytoplankton cells in early May in 2006, in late June in 2013, and in early May in 2015. The ice breakup during these years occurred at the end of June in 2006 and in 2013 and at the end of April/beginning of May in 2015. These preliminary results suggest that the timing of the ice algae release/phytoplankton bloom is not directly linked to ice melt but possibly to snow melt, as seen in under-ice export fluxes obtained in Baffin Bay. Additional sediment trap samples from the Beaufort Sea will be analyzed in the coming months to investigate this pattern.

Arctic underwater noise transients from sea ice deformation: Characteristics, annual time series, and forcing in Beaufort Sea (Kinda, Bazile, Gervaise, Mars, and Fortier)

A 13-month time series of Arctic Ocean noise from the marginal ice zone of the Eastern Beaufort Sea is analyzed to detect under-ice acoustic transients isolated from ambient noise with a dedicated algorithm. Noise transients due to ice cracking, fracturing, shearing, and ridging are sorted out into three categories: broadband impulses, frequency modulated (FM) tones, and high-frequency broadband noise. Their temporal and acoustic characteristics over the 8-month ice covered period, from November 2005 to mid-June 2006, are presented and their generation mechanisms are discussed. Correlation analyses showed that the occurrence of these ice transients responded to large-scale ice motion and deformation rates forced by meteorological events, often leading to opening of large-scale leads at main discontinuities in the ice cover. Such a sequence, resulting in the opening of a large lead, hundreds by tens of kilometers in size, along the margin of landfast ice and multiyear ice plume in the Beaufort-Chukchi seas is detailed. These ice transients largely contribute to the soundscape properties of the Arctic Ocean, for both its ambient and total noise components. Some FM tonal transients can be confounded with marine mammal songs, especially when they are repeated, with periods similar to wind generated waves (Kinda et al., 2015).

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

Continuous bi-weekly to bi-monthly dinoflagellate cyst, tintinnid loricae and tintinnid cyst fluxes were measured at two mooring sites in Hudson Bay (subarctic Canada) from October 2005 to September 2006. The total dinoflagellate cyst fluxes at the site on the western side of the bay ranged from 4600 to 53,600 cysts m^{-2} day^{-1} (average 20,000 cysts m^{-2} day^{-1}), while on average three times higher fluxes (average 62,300 cysts m^{-2} day^{-1}) were recorded at the site on the eastern side of the bay with a range from 2700 to 394,800 cysts m^{-2} day^{-1}. These values are equivalent to the average fluxes calculated from the top 1-cm sediment layer of ^{210}Pb-dated box cores at corresponding locations, and hence lend support to the use of sediment dinoflagellate cysts in paleoceanography. Tintinnid fluxes ranged from 1200 to 80,000 specimen m^{-2} day^{-1} (average 32,100 tintinnids m^{-2} day^{-1}) in the west, and 1600 to 1,240,800 specimen m^{-2} day^{-1} (average 106,800 tintinnids m^{-2} day^{-1}) in the east, with the highest *Salpingella* sp. fluxes recorded during the sea-ice cover season. The dinoflagellate cyst species diversity recorded in the traps was similar at the two environmentally differing locations, with cold-water (e.g., *Echinidinium karaense, Islandinium minutum*, *Islandinium? cezare, Polykrikos* sp. var. *arctica*, *Spiniferites elongatus*), cosmopolitan (e.g., *Operculodinium centrocarpum, Spiniferites ramosus, Brigantedinium*) and typical warmer-water (e.g., *Echinidinium aculeatum, Islanidium brevispinosum*) species present. Furthermore, the species-specific timing of cyst production behaved similarly relative to the seasonal sea-ice cycle at both locations. Cyst species proportions and species-specific flux quantities, however, differed between the two sites and corresponded to the quantities and species assemblages recorded in the surface sediment, with the exception of cysts of *Polarella glacialis* and cf. *Biecheleria* sp. that seem not to preserve well in sediment but were abundant in both traps. Otherwise, cyst assemblage at the western trap site was dominated by *Operculodinium centrocarpum* and *Spiniferites elongatus* while at the eastern site very high quantities of cysts of *Pentapharsodinium dalei* were recorded. Our data does not lend support to the hypothesis of trophic status as the determinant of cyst production in the open water versus ice-covered conditions, since cysts of light-dependent (autotrophic) and dark-adapted (heterotrophic) dinoflagellates are recorded equally around the ice breakup and during the open-water season.

Downward particle flux and carbon export in the Beaufort Sea, Arctic Ocean; the role of zooplankton (Miquel, Gasser, Martin, Marec, Babin, Fortier, Forest)

As part of the international, multidisciplinary project Malina, downward particle fluxes were investigated by means of a drifting multi-sediment trap mooring deployed at three sites in the Canadian Beaufort Sea in late summer 2009. Mooring deployments lasted between 28 and 50 h and targeted the shelf-break and the slope along the Beaufort-Mackenzie continental margin, as well as the edge between the Mackenzie Shelf and the Amundsen Gulf. Besides analyses of C and N, the collected material was investigated for pigments, phyto- and microzooplankton, faecal pellets and swimmers. The measured fluxes were relatively low, in the range of 11–54 mg m^{-2} d^{-1} for the total mass, 1–15 mg C m^{-2} d^{-1} for organic carbon and 0.2–2.5 mg N m^{-2} d^{-1} for nitrogen. Comparison with a long-term trap data set from the same sampling area showed that the short-term measurements were at the lower end of the high variability characterizing a rather high flux regime during the study period. The sinking material consisted of aggregates and particles that were characterized by the presence of hetero- and autotrophic microzooplankters and diatoms and by the corresponding pigment signatures. Faecal pellet contribution to sinking carbon flux was important, especially at depths below 100 m, where they represented up to 25 % of the total carbon flux. The vertical distribution of different morphotypes of pellets showed a marked pattern with cylindrical faeces (produced by calanoid copepods) present mainly within the euphotic zone, whereas elliptical pellets (produced mainly by smaller copepods) were more abundant at mesopelagic depths. These features, together with the density of matter within the pellets, highlighted the role of the zooplankton community in the transformation of carbon issued from the primary production and the transition of that carbon from the productive surface zone to the Arctic Ocean's interior. Our data indicate that sinking carbon flux in this late summer period is primarily the result of a heterotrophic-driven ecosystem.

DISCUSSION

Even though many interesting studies have already been published with the results obtained during the previous phases of the LTOO project, further measurements of the composition of the export fluxes along with a synthesis of all the physical and biogeochemical data obtained in the last decade during ArcticNet's last phase will certainly provide crucial information on changes occurring on a longer time scale in the Arctic Ocean. Already, preliminary results on the composition of the phytoplankton and zooplankton collected in several sediment traps deployed over the past 10 years in the Beaufort Sea showed interesting patterns that will be correlated with water temperature, sea ice, and snow cover in the region.

Such long-term measurements are rare in the Arctic Ocean. In the eastern Arctic Ocean, the HAUSGARTEN observatory has been maintained for more than a decade by the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research to monitor the impact of large-scale environmental changes on downward export fluxes and benthic communities in the Fram Strait (Soltwedel et al., 2005; Lalande et al., 2013). These long-term measurements showed that the composition of the biogenic matter exported out of the upper ocean vary temporally depending on the temperature of the Atlantic Water inflow and on the presence of ice cover in the eastern Fram Strait, with enhanced export fluxes of larger phytoplankton cells generally observed when sea ice is concurrently present with sunlight in the area (Bauerfeind et al., 2009; Lalande et al., 2013). The passing of a warm anomaly in the eastern Fram Strait also led to a lower export of smaller zooplankton fecal pellets, and to a northward displacement of sub-arctic and temperate zooplankton species (Bauerfeind et al., 2009; Kraft et al., 2011; Lalande et al., 2013; Soltwedel et al., in press). Long-term measurements obtained through the LTOO project will enable us to investigate the impact of warmer conditions in the western part of the Arctic Ocean, and to compare the changes recorded to observations made in the Fram Strait. This information will be essential to assess how the impact of climate change will vary in the different regions of the Arctic Ocean.

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

CONCLUSION

Overall, the continuation and synthesis of the existing decadal records of physical and biogeochemical signals obtained through the LTOO project provides invaluable information on the impact of climate change in the Arctic Ocean. The results obtained within the LTOO project represent the Canadian contribution to long-term monitoring in the Arctic Ocean and enable many international collaborative studies. Although the time series developed until now provide some insight into the state of the environment, the impacts of climate change in the Arctic will take a few decades to fully emerge. It is therefore crucial to maintain the observatories to build the long-term dataset needed to answer the ecosystem-level questions raised by climate change.

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Integrated Marine Geoscience to Guide Environmental Impact Assessment and Sustainable Development in Frobisher Bay, Nunavut

Project Leader

Evan Edinger (Memorial University of Newfoundland)

Network Investigators

Alec Aitken (University of Saskatchewan)
Vaughn Barrie (Natural Resources Canada - Geological Survey of Canada (Pacific))
Trevor Bell (Memorial University of Newfoundland)
Calvin Campbell (Dalhousie University)

Collaborators

Randy Gillespie (Memorial University - Marine Institute)
Linda Ham (Canada Nunavut Geoscience Office)
Janelle Kennedy (Fisheries and Sealing Division, Department of Environment)
David Mate (Natural Resources Canada - Geological Survey of Canada)
Jamal Shirley (Nunavut Research Institute)

HQP

Robert Deering, Doctoral Student (Memorial University of Newfoundland)
Nature and triggers of submarine mass failure in coastal waters of southeastern Baffin Island, Nunavut
Ben Misiuk, Doctoral Student (Memorial University of Newfoundland)
Mapping Clam Habitat in the Arctic: Baseline Data for Fisheries Assessment and Management
Kendra Zammit, Honours Undergraduate Student (Memorial University of Newfoundland)
Laura Broom, Technical Staff (Dalhousie University)
Erin Herder, Technical Staff (University of Saskatchewan)
Lara Miles, Technical Staff (Memorial University of Newfoundland)
Kirk Regular, Technical Staff (Memorial University - Marine Institute)
André Roy, Technical Staff (Memorial University - Marine Institute)
Roxanne Van Velzen, Undergraduate Student (Memorial University of Newfoundland)

Northern HQP

Manasie Kendall, Northern Student (Memorial University of Newfoundland)
Alex Kilabuk, Northern Student (Nunavut Arctic College)

ABSTRACT

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

KEY MESSAGES

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

OBJECTIVES

The objectives of this project are to:

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

Specific objectives for 2015 were to:

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

- Map small side fjords on the south side of outer Frobisher Bay along gradients of slope, proximity to active glaciers, and relative sea level trend, to gather data with which to better understand the driving forces behind submarine slope failures in Arctic fjords.
- Map heads of submarine landslides that were previously identified but not completely mapped in Inner Frobisher Bay.
- Initiate resampling of long-term ecology study sites in Inner Frobisher Bay.
- Initiate ground-truthing of bottom types identified from multibeam sonar in Inner and Outer Frobisher Bay..

INTRODUCTION

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

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

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

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

1. Biological habitat mapping. Biological habitat mapping estimates the distribution and composition of habitat types around the bay, relying on the close links between bottom geomorphology and benthic biology (Brown et al. 2011, Harris 2012, Copeland et al. 2012). Characterizing and mapping habitats also allows us to identify sensitive habitats that might need to be protected from expanding fisheries or infrastructure development.
2. Long-term ecological study. We are re-sampling biological monitoring sites in Inner Frobisher Bay that were first studied in the late 1970’s (Wacasey et al. 1979, 1980; Cusson et al. 2007).

Resampling these sites, and placing the habitats they represent within their context for the bay, allows us to estimate long-term changes in benthic communities that could accompany climate change, and to distinguish long-term directional change from short-term fluctuations (e.g. Hofmann et al. 2013).

3. Marine geohazard characterization and mapping. Inner Frobisher Bay appears to have an anomalously high incidence of submarine slope failures, which are readily mapped using multibeam sonar (cf. Campbell et al. 2014). Our research in Frobisher Bay maps these submarine landslides, but more importantly characterizes the slide morphology, and uses piston cores to understand the triggering mechanisms and recurrence interval of these natural disturbance events. Understanding the size and recurrence interval of these events, along with slope stability studies, is crucial baseline information for guiding infrastructure development. Other geological hazards in Inner Frobisher Bay include ice scour and possible tsunamis (Hatcher and Forbes 2015).

4. Seabed characterization. Seabed characterization throughout Frobisher Bay provides crucial information to guide development decisions. Rapid sedimentation in the macrotidal setting of Frobisher Bay already pre-conditions the bay for sediment instability. Slope stability studies, penetrometer tests, and other geotechnical assessment of the seabed in Inner Frobisher Bay, combined with the multibeam sonar mapping, provide important baseline information for coastal engineering projects associated with infrastructure development.

ACTIVITIES

Dissemination of scientific results

- Presentations (oral and poster) have been given at national and international conferences (Canadian Quaternary Association 2015, 45th Arctic Workshop, 36th Canadian Symposium on Remote Sensing, ArcticNet Annual Scientific Meeting 2015, American Geophysical Union fall meeting), relating to the work on submarine slope failures in Frobisher Bay.
- Inclusion of ArcticNet imagery and preliminary results from Frobisher Bay in a presentation on Arctic carbonates (Edinger, keynote, 1st International Carbonate Mounds Conference, Monte Verità, Switzerland), and in a summary of biological findings from the 2015 *Amundsen* ROV expedition at the March 2016 Benthic Ecology Meeting.
- Summary of 2015 mapping results from 2015 to be published in CNGO Summary of Activities (cf. Mate et al. 2015).

HQP training

- Two new MSc students recruited in 2015-2016, to start in May 2016 (Erin Herder, Laura Broom). Both of these students currently employed as research assistants on the project.
- Two new PhD students started in Sept 2015 (transferred from MSc studies): Robert Deering, Benjamin Misiuk.
- Nunavut Arctic College student involved in 2015 field sampling as part of Environmental Technology training program.
- One undergraduate honours student recruited, to start May 2016 (Kendra Zammit).
- One undergraduate research assistant hired (Jordon Rozon, University of Saskatchewan).

Field work in the Canadian Arctic in 2015

- Joint ArcticNet/GSC cruises on the MV *Nuliajuk*, multibeam mapping, ground-truth sampling. Approximately 655 km^2 were mapped in Frobisher Bay aboard MV *Nuliajuk*.
- ROV dive, piston coring and multibeam mapping aboard CCGS *Amundsen*.

- Two piston cores were recovered from the Hill Island submarine slope failure complex and adjacent undisturbed seafloor (witness core) in Inner Frobisher Bay.
- One location in Frobisher Bay was surveyed using the SuMo ROV during the CCGS *Amundsen* 2015 expedition, on the site of an underwater landslide near Hill Island, in Inner Frobisher Bay. The primary activity was the acquisition of video data.
- Carbonate bioclasts from Inner Frobisher Bay were collected for pilot study on cold-water carbonate sediments in the Canadian Arctic.
- Extensive planned Geological Survey of Canada cruise in Baffin Bay and Frobisher Bay aboard CCGS *Hudson* planned for 2015 was cancelled due to corrosion of the ship. This mission would have carried out extensive piston coring, grab sampling of bottom types and bottom biota, and multibeam mapping at night using a pole-mounted multibeam system. A postponed expedition is planned for 2017.

Laboratory work, instrumentation, analysis

- Post-cruise processing of multibeam sonar data ongoing at MUN and MUN Marine Institute.
- Video transects from 2015 expedition have been analyzed at MUN (see results, and Miles et al. 2015).
- Benthic samples from 2015 expedition under analysis at University of Saskatchewan.
- Analysis of 2015 piston cores has been completed at the Bedford Institute of Oceanography. Observations and measurements included visual core description, split core x-radiography and photography, shear strength, gamma density, p-wave velocity, electrical resistivity, magnetic susceptibility and colour spectrophotometry. Subsamples were collected for grain size analysis, clast lithology and radiocarbon dating.

Other activities

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

RESULTS

Mapping aboard MV Nuliajuk

Approximately 655 km^2 were mapped in Frobisher Bay during the MV *Nuliajuk* combined Legs 1a, 2, 4 and 5 (Figure 1) despite extremely challenging ice conditions during Leg 1a and (to a lesser extent) Leg 2. Unusually heavy sea ice in Outer Frobisher Bay in late July and much of August 2015 confined Leg 1 mapping efforts to the side fjords along the southwestern edge of Outer Frobisher Bay (see figure 2). The side fjords mapped were Jackman Sound, York Sound, Watts Bay, Delano Bay, Leach Bay, and Kneeland Bay. Sub-bottom profiles were acquired while mapping all of these areas. These six side fjords

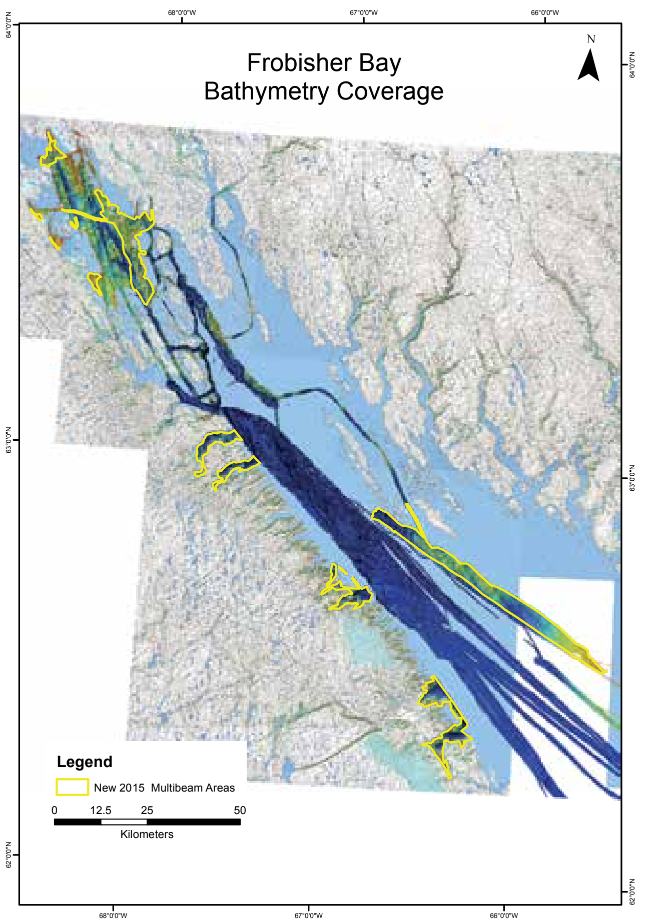

Figure 1. Map showing areas surveyed using multibeam sonar in 2015, outlined in yellow. The side bays along the southwest margin of the bay were surveyed in late July and early August, when ice conditions prevented access to other portions of the bay. The large polygon in the Northeast of the bay was surveyed in Leg 4. Additional areas of the Inner bay were surveyed in Legs 2 and 5.

were chosen to fall along gradients in slope, proximity to the active, but rapidly retreating Grinnell and Terra Nivea glaciers (Way 2015), and relative sea level trend, to gather data with which to better understand the driving forces behind submarine slope failures in Arctic fjords. Jackman Sound and York Sound have gently sloping side walls, while Watts Bay and Delano Bays are more steep-walled, as are Leach and Kneeland Bays. Leach Bay and Kneeland Bay are far from the glaciers, and being further inland along Frobisher Bay, are more likely to be experiencing relative sea level fall. Leach Bay and Kneeland Bay were not part of the original cruise plan, but were added when ice conditions prevented the ship from mapping the NE or NW moraines targets, or from transiting between the mid-bay islands to Iqaluit for the crew change before Leg 1b. Ice conditions in the mid-bay islands still trapped the ship in ice near Daniel Island for three days, before the ship was escorted to Iqaluit by the Coast Guard icebreaker CCGS *Des Grosseillers* (Figure 2).

Mapping in the Southwest Outer Frobisher Bay fjords did not reveal additional extensive submarine slope failures, in contrast with Inner Frobisher Bay, where submarine landslides are abundant.

The quality of the bathymetric data collected is quite high, with other relatively small features including submarine channels readily identified, so it is unlikely that any slope failures were missed. Other features were identified, including submerged channels and iceberg wallow (Figure 3), indicating that had submarine slope failures been present, they would have been identified.

Additional submarine slope failures were identified within Inner Frobisher Bay, such as this newly discovered slide near Frobisher's Farthest (Figure 4). This underwater landslide occurred between approximately 45 and 100 m depth, with a run-out length of approximately 800 m.

Other interesting glacial features discovered included a probable esker observed near Cape Rammelsberg, where we expected to find the offshore continuation of a moraine previously mapped on land (Figure 5).

Field sampling aboard MV Nuliajuk (A. Aitken, L. Miles, A. Kilabuk)

Field sampling aboard MV *Nuliajuk* had two purposes: to ground-truth multibeam sonar geologically and biologically, and to re-sample long-term ecology sites near Iqaluit in Inner Frobisher Bay. Targets for ground-truthing sampling were chosen before the

Figure 2. CCGS Des Grosseillers escorting MV Nuliajuk through heavy ice towards Iqaluit.

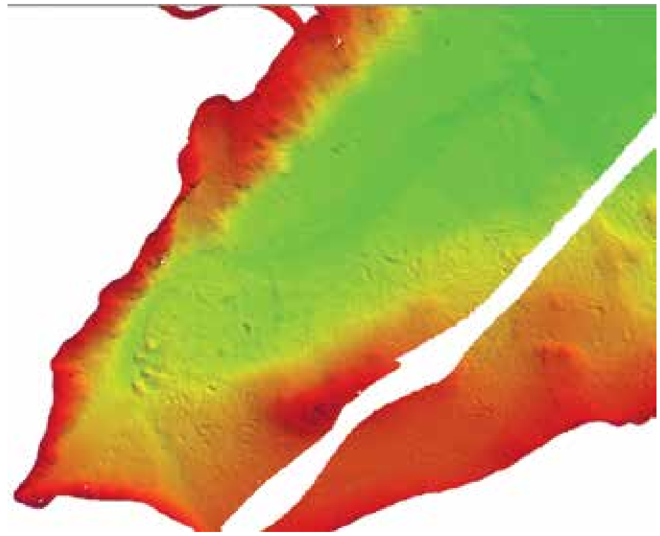

Figure 3. Uncleaned, unmerged high-resolution multibeam bathymetry from the nearshore area of York Sound, southwest outer Frobisher Bay. Note sinuous (possibly submerged?) channel, approx. 2 km long, and iceberg wallow features. Strip of missing data in this image filled on a different mapping day, but datasets not yet merged. No obvious slope failures were mapped in York Sound or Jackman Sound.

beginning of Leg 1a, using the existing multibeam sonar data collected in 2012-2014. Twenty ground-truthing locations were sampled in 3 days of sampling aboard *Nuliajuk*. Sampling aboard *Nuliajuk* used the Van Veen grab sampler and the Deep Blue SplashCam underwater drop video camera, until the camera cable began to fail upon submersion (Figure 6). Eight stations were sampled with both grab and video, and the remaining 11 stations were sampled with grab sampler only. At each sampling station, two replicate ten minute drop-video camera tows preceded the grab sampling. Grab sampling included at least three attempted grabs from each station. The contents of each grab sample were photographed. From the grab samples recovered, two duplicate 125 ml subsamples of sediment were collected and frozen for later analysis, before the remaining sediment was sieved through a 1 mm mesh screen. All flora and fauna were fixed in 10% formalin in seawater, before being transferred to 70% ethanol in seawater. Major sampling targets for ground-truthing included the submerged portion of the moraine mapped on land near Lewis Bay, a large slope failure near Hill Island, and low-backscatter features identified near Hill Island. Sampling was interrupted on August 13 to repair the grab sampler, and could not be resumed on Aug 14 due to fog, rending navigation in Inner Frobisher Bay unsafe.

In addition, eight long-term ecology sites near Iqaluit were sampled with a grab sampler from a 22’ open deck fishing boat on August 8, 2015, while the *Nuliajuk* was trapped in the ice near Daniel Island. This sampling was challenged by poor penetration of the grab sampler into the bottom sediment, and ultimately by the loss of the grab sampler release pin.

Particularly interesting findings included confirming the diamicton composition of the suspected moraine near Lewis Bay, and documenting abundant and diverse epifauna on this moraine (Figure 7). Other prominent epifauna observed in the bay included abundant crinoids, large erect tunicates, abundant sponges, and two types of soft corals (Figure 7). One site had abundant euphasid crustaceans to the point that other fauna could not be seen in video. Abundant and diverse sponges were sampled near Hill Island.

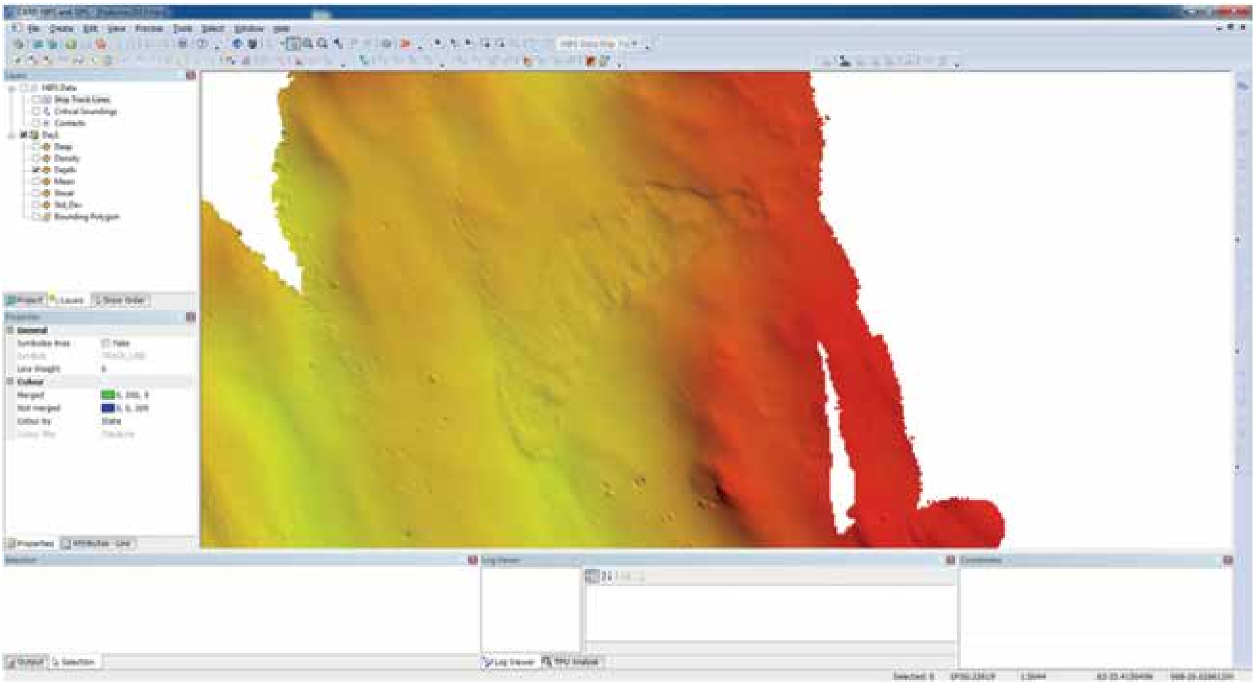

Figure 4. Screencapture of submarine landslide near Frobisher's Farthest, Inner Frobisher Bay, during multibeam sonar acquisition late August, 2015. 63°35.42' N / 068°20.02'W. The slide began in about 45 m water depth, and ended in about 100 m depth; runout length is approximately 800 m. White streaks on the image are artifacts that will be removed during data cleaning and postprocessing.

Most of the muddy-bottom sites sampled by drop video camera in 2015 were below the photic zone, hence were dominated by fauna, rather than flora. Bottom fauna in the sites sampled by drop video camera were generally dominated by orphiuroid echinoderms (brittle stars), sponges and tunicates (Figure 8). Crinoids (feather stars) were among the dominant sedentary epifauna on two sites. Extremely abundant arthropods in several sites included amphipods and euphausid krill.

Detailed faunal analysis of grab sampled biota is ongoing.

ROV dive results aboard CCGS Amundsen (ROV research group)

SuMo Dive 48: Hill Island, Inner Frobisher Bay (63.6385994 N, -68.6306992 W) October 25th 2015

The dive started at 139 m depth in a soft bottom area outside of the landslide, where ascidians (*Ciona intestinalis*) were very abundant, forming fields. Echinoderms and isopods were frequently seen, including isopods with juveniles clustered on the front appendages of the adults. Large concentrations of kelp were observed, although it is undetermined whether the kelp is resident to the site or from shallower depths.

Brittle stars and feather stars were the dominant organisms in the landslide area, along with sponges (Desmospongia), while ascidians were much less abundant. In the landslide area crinoids were more abundant where slope was higher. The sea star *Solaster* cf. e*ndeca* was also observed in this part of the dive.

The landslide ridges observed in the bathymetry could be identified during the transect as changes in the slope. Sporadic boulders were encrusted with soft corals (few), sponges, crinoids and tube polychaetes. Fish (eel pout, sea tadpoles, and sculpins) were also

Figure 5. Unprocessed bathymetric image collected near Cape Rammelsberg, Inner Frobisher Bay. Linear feature running NWSE through image is probably an esker, running approximately 1.6 km in this image, and approximately 30 m high. 63°24.5 N / 068°21.5W. Origins of round pits yet to be determined.

observed. Juvenile scallops were also abundant in this part of the transect, with densities of at least 24 individuals/m^2. Picnogonids were also conspicuous in the landslide area.

After surveying the landslide area, we went back to the beginning of the dive in order to sample ascidians, and to give continuity to the transect in a high slope area. One globular sponge, one ascidian, and one arborescent sponge were successfully sampled using the ROV arms. Because the samples were kept in the ROV arm, only fragments of the arborescent sponge could be retrieved. The globular sponge had a peculiar garlic smell.

In the second part of the transect we surveyed the transition zone between a flat bottom environment and a rocky outcrop. A high concentration of ascidians and sponge gardens (dominated by arborescent sponges) were observed in this part of the dive, as well as crustaceans (isopods), sea cucumbers (probably *Psolus fabrici*), crinoids, ophiuroids, sea stars, sea anemones, and tube polychaetes (Figure 9). Fish were also seen throughout the dive, including a juvenile flatfish, alligator fish, and sea tadpoles.

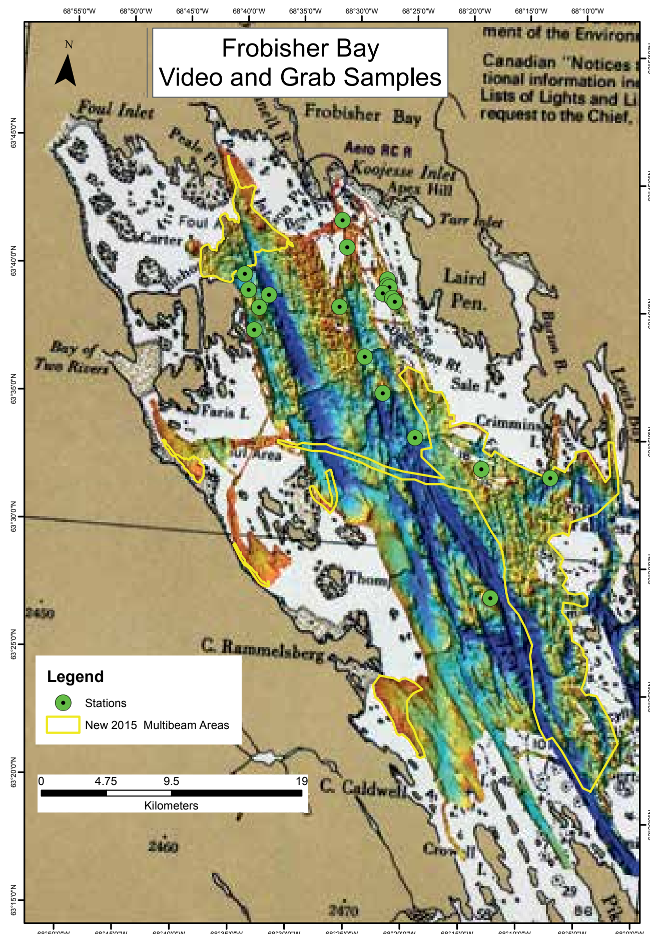

Figure 6. Location of benthic sampling stations within Inner Frobisher Bay, August 2015. Long-term ecology sites are in the north, close to Iqaluit, while the Hill Island landslide site is in the west.

Piston Coring (R. Deering, T. Bell, C. Campbell)

A 6-m-long sediment core from one lobe of the Hill Island submarine slope failure complex revealed a sequence of disturbed marine sediments (Figure 10) overlying *in situ* and undisturbed sediment, indicating that the core penetrated the décollement plane of the failure event. The character of the disturbed sediments will provide insights into the nature of the slope failure processes and the susceptible materials involved. Radiocarbon dates on carbonate shells sampled from the core will bracket the failure event and help build a local chronostratigraphy for inner Frobisher Bay. A

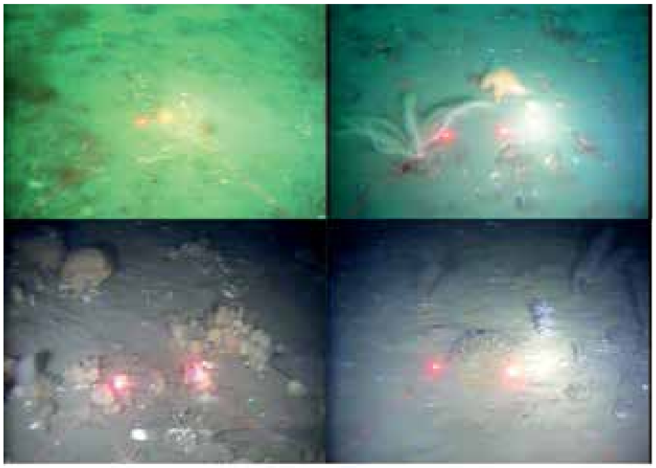

Figure 7. Photomontage of video results from Frobisher Bay sampling. Upper left: Station 1a: Laminaria kelp, abundant sponges and crinoids. Upper right: Station 2: Piaster sea star abundant crinoids. Lower Left: Station 6: Lewis Bay moraine site, abundant and diverse sponges and crinoids. Lower Right: Station 2A: unusual sponge fauna with soft corals and tubular ascidians. Laser points 10 cm apart in all images.

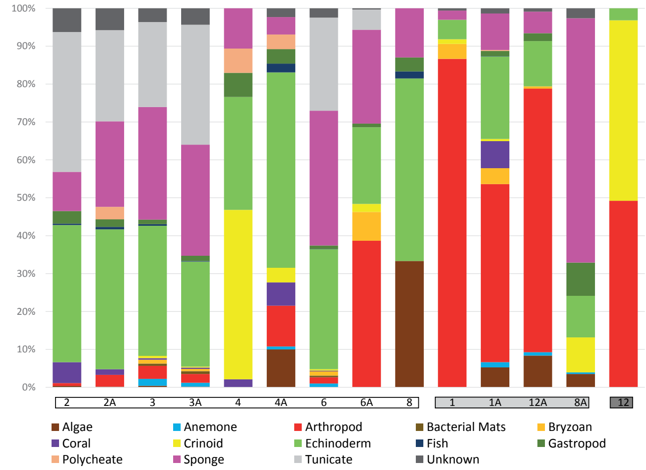

Figure 8. Percent abundance per faunal group at sites sampled with bottom video in 2015. Sites colour-coded by grain size: muddy bottoms (white), muddy gravel (grey), gravel bottoms (black).

2014 piston core from an adjacent lobe of the same Hill Island failure complex indicates that the seafloor failure was active at some time after 5000 BP. Upon examination, a 5-m-long core originally recovered to represent undisturbed seafloor sediments (witness core) revealed disturbed sediments similar to the core from the slope failure footprint. This unexpected result may be simply explained by inaccurate targeting of undisturbed seafloor during the coring process; we are re-examining the ship navigation files to test this hypothesis.

Extensive piston coring of submarine slope failures and glacial features, among other targets, was meant to occur aboard a Geological Survey of Canada cruise on *CCGS Hudson*. Owing to issues with the vessel this did not occur, limiting coring activities for this season to one day aboard *CCGS Amundsen*.

Multibeam sonar mapping aboard CCGS Amundsen

Two areas of Outer Frobisher Bay were to have been mapped by CCGS *Amundsen* during the 2015 mission: a deep-water polygon in northwestern outer Frobisher Bay, and an along-track swatch along the southeastern edge of outer Frobisher Bay. Both of these mapping efforts were planned for the 2015 Amundsen Leg 4c, but the polygon was cancelled due to high seas (6 m swell). The along-track swath collected partially connects the existing deep-water coverage from the *Amundsen* with the newly acquired 2015 shallow water coverage from MV Nuliajuk. The remainder of this gap will be closed during the 2016 *Amundsen* expedition. Completing the coverage between the shallow mapping in side fjords and the main part of Outer Frobisher Bay will allow us to examine continuity of submerged landforms and to identify any slope failures associated with the steepest parts of the (apparently) fault-bounded southeastern margin of Outer Frobisher Bay.

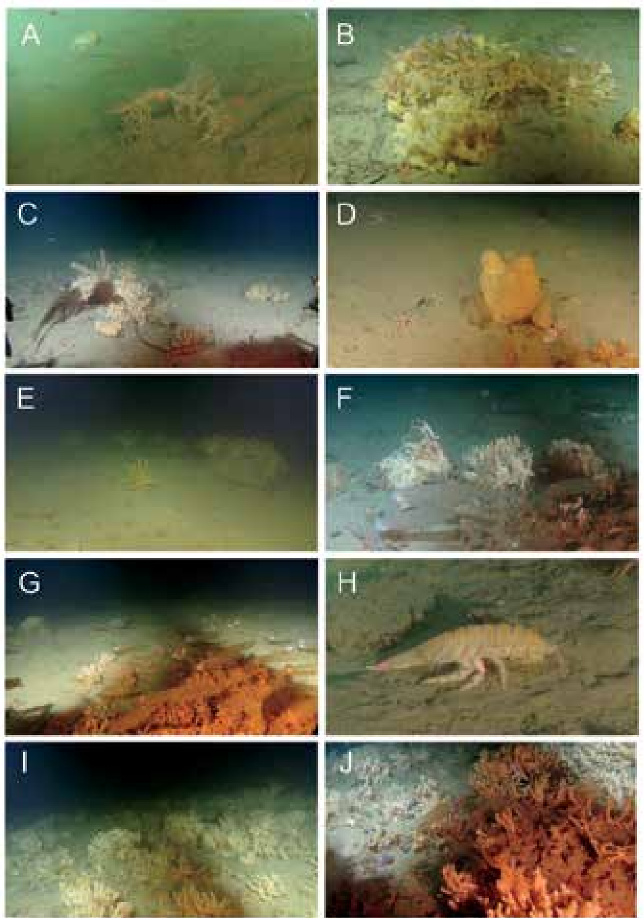

Figure 9. Organisms and bottom types observed during the ROV dive at Frobisher Bay. A) isopod with juveniles, B) crinoids, C) sponges, crinoids and kelp, D) large yellow sponge, E) crinoids, F-G) ascidians and sponges, H) large isopod, I-J) sponge gardens (mostly the fan sponge). Red lasers are 10 cm apart.

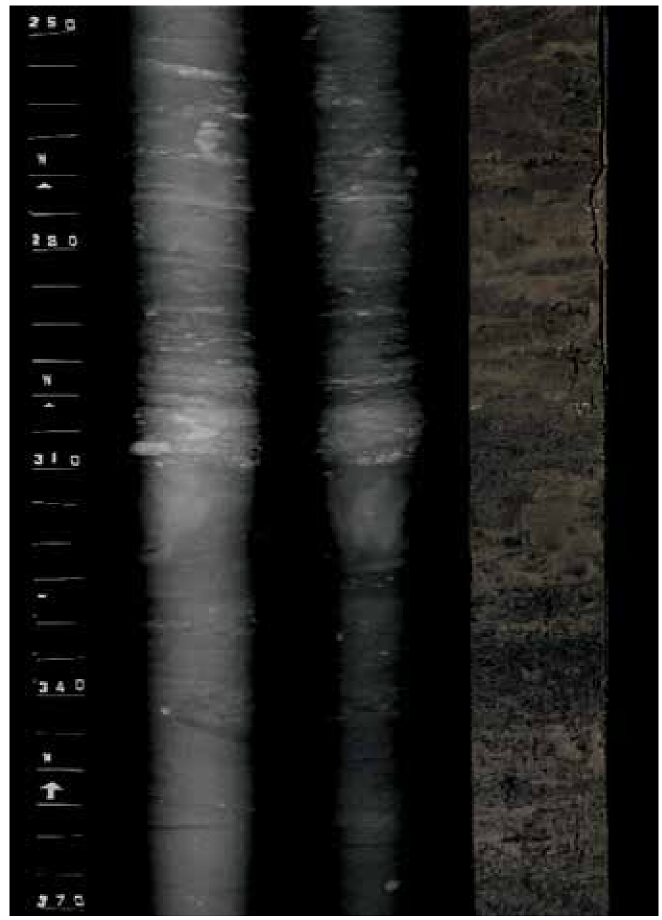

Figure 10. Photograph (right) and X-radiograph (left) of a section (250-370 cm) of piston core 2014805-0004 showing disturbed sediments related to seafloor slope failures near Hill Island in inner Frobisher Bay.

DISCUSSION

Geohazards & submarine landslide typology

Inner Frobisher Bay presents a rare opportunity to investigate small-scale submarine slope failures (SSF) in an Arctic coastal embayment. To date we have mapped in excess of 250 SSF in the inner bay. Since their abundance in the region was first discovered (Mate et al., 2015), their potential impact on coastal and marine infrastructure projects has been recognized. For example, two seabed cable-laying companies have approached us to collaborate and share our results. We are creating an inventory of relict SSF in the inner bay in order to better understand where and how these events occur. Our morphometric analysis of this database follows a similar study conducted by Pinet et al. (2015) in the St. Lawrence River Estuary.

Our piston cores from 2014 and 2015 provide some intriguing initial results. The preliminary observation (based on a single failure) that the Hill Island SSF is younger that 5000 BP is important because our current understanding of submarine slope failures would assume a much earlier chronology linked to deglaciation of Frobisher Bay around 7000 BP (Lee, 2009). The possibility that these seafloor failures were triggered more recently in the postglacial highlights macro-tidal forcing mechanisms as a potential causative factor and introduces the possibility that they continue to be active today. We are developing new approaches to sampling and dating SSF events in inner Frobisher Bay as conventional methods (e.g. Urlaub et al., 2013) are challenging given the sheer number. For example, differences in the thickness of undisturbed sediments overlying SSF deposits in piston cores from the primary and secondary lobes of the Hill Island SSF indicate different relative ages of failure activity. If we can establish a consistent sedimentation rate for these deposits, then we can extrapolate the age of a SSF based on the thickness of *in situ* sediments overlying disturbed sediments.

The unanticipated stratigraphy in the witness core collected adjacent to Hill Island SSF in 2015, assuming the core location is true, may have several explanations: 1) the core location experienced a slope failure event, the seafloor evidence for which was subsequently buried by post-failure sedimentation; 2) the main Hill Island slide produced compressive disturbance of seafloor sediments beyond its toe that is not visible on the seafloor bathymetry today, or 3) the Hill Island slide is still active today and the slide footprint has expanded since the multibeam survey. Change detection of repeat multibeam surveys of the slide will test the third hypothesis, whereas analysis of acoustic sub-bottom profiles should reveal the occurrence of buried failed sediments assumed in hypotheses 1 and 2.

Habitat mapping for biodiversity

The moraines and eskers documented in Inner Frobisher Bay, and probably observed in Outer Frobisher Bay, were observed where they were expected, based on offshore continuations of similar features previously mapped on land. It is not uncommon to find submerged moraines and other glacial features in fjords, where they can support distinct habitat types (e.g. Copeland et al. 2012). The moraine sites harboured distinctive biological assemblages from the muddier-bottom sites.

The high abundance and diversity of sponges encountered in the drop video, grab samples and ROV dive from Inner Frobisher Bay emphasizes the importance of Frobisher Bay in supporting benthic biodiversity. Additionally, erect bryozoans, also identified as vulnerable marine ecosystem (VME) taxa by the Northwest Atlantic Fisheries Organization (NAFO) were observed in Frobisher Bay, both live and as carbonate bioclasts. These results emphasize the importance of documenting sensitive habitat types in Frobisher Bay prior to fisheries development in the Bay (cf. Christensen et al. 2013), or other activities that could disturb the seabed. The apparently reduced diversity of seabed fauna in the path of a natural disturbance from a submarine slope failure is an important result. Detailed video analysis over the winter will carefully quantify this initial apparent result. The ecologically old, though geologically young, age for the Hill Island slide implies the possibility of very long-lasting impacts of natural or anthropogenic physical disturbance on Arctic benthic communities. These preliminary suggestions will require more careful data analysis, and replication at other submarine landslide sites.

Long-term ecology

Several sites (i.e., Long-Term Ecology Sites or LTES, Figure 6) were occupied in August, 2015 to re-sample sites previously studied in the 1970's and 1980's to assess long-term variation in species composition and abundance, and to map the extent of the habitat types represented by these long-term study sites. Historical data, based on grab and dredge sampling, at these locations revealed a diverse benthic fauna dominated by mollusks, brittle stars, amphipod crustaceans and polychaetes (Wacasey et al., 1979, 1980). Longitudinal studies of benthic community structure in the Canadian Arctic are virtually non-existent. The few published studies that appear in the peer-reviewed research literature include Conlan and Kvitek (2005; reporting the colonization of the ice-scoured seafloor of Barrow Strait over several decades) and Cusson et al., (2007; reporting on temporal variations in benthic community structure in Frobisher Bay). In the context of rapid environmental change in circumpolar marine ecosystems (e.g., Wassmann, 2008; Renaud et al., 2008) it has become imperative to more thoroughly document spatial and temporal variations in benthic community structure to create a baseline from which future changes can be assessed. Biological sampling and mapping of seabed habitats will characterize macro- and megafauna biodiversity and identify sensitive habitats that might require protection during infrastructure and resource development projects or possible fisheries within Frobisher Bay.

CONCLUSION

Field sampling in Frobisher Bay in 2015 involved four major activities: acquisition of multibeam sonar data from MV *Nuliajuk* and CCGS *Amundsen*, bottom grab sampling and drop video sampling from MV *Nuliajuk*, piston coring from MV *Nuliajuk*, and ROV dive from CCGS *Amundsen*. All four sampling approaches yielded valuable information about seabed composition, natural seabed disturbances, and benthic biological assemblages.

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Innovative Research on Monitoring Marine Mammals to Mitigate Impacts of a Changing Arctic

Project Leader

Steven Ferguson (University of Manitoba)

Network Investigators

Andrew Derocher (University of Alberta)
Mike Hammill (Université du Québec à Rimouski)

Collaborators

David G. Barber (University of Manitoba)
Rudy Boonstra (University of Toronto)
Markus Dyck (Government of Nunavut)
Aaron Fisk (University of Windsor)
Keith Hobson (University of Saskatchewan)
William Koski (LGL Limited - Environmental Research Associates)
Nick Lunn (Environment Canada)
Martyn Obbard (Ontario Ministry of Natural Resources)
Evgeny Pakhomov (University of British Columbia)
Stephen Petersen (Fisheries and Oceans Canada - Freshwater Institute)
Jodie Pongracz (University of Alberta)
Evan Richardson (Environment Canada)
Ann Tarrant (Woods Hole Oceanographic Institute (WHOI))

HQP

Cassandra Debets, Doctoral Student (University of Manitoba)
Sarah Fortune, Doctoral Student (University of British Columbia)
Evaluating the energetic consequences of environmental change for bowhead whales in the Eastern Canadian Arctic
Amy Johnson, Doctoral Student (University of Alberta)
Jody Reimer, Doctoral Student (University of Alberta)
Dave Yurkowski, Doctoral Student (University of Manitoba)
Behavioural responses of ringed seals (Pusa hispida) to environmental variability in a changing Arctic ecosystem
Katie Florko, Honours Undergraduate Student (University of Winnipeg)
Justine Hudson, Honours Undergraduate Student (University of Winnipeg)
Karyn Booy, Masters Student (University of Manitoba)
Ellyn Davidson, Masters Student (University Centre of the Westfords)
Maha Ghazal, Masters Student (University of Manitoba)
Krista Kenyon, Masters Student (Centre for Earth Observation Science (CEOS))
Ron Togunov, Masters Student (University of Alberta)
Michelle Viengkone, Masters Student (University of Alberta)
Spatial genetics of Hudson Bay polar bears
Thea Bechshoft, Post-Doctoral Fellow (University of Alberta)
Cory Matthews, Post-Doctoral Fellow (University of Manitoba)
Nick Pilfold, Post-Doctoral Fellow (University of Alberta)
Corinne Pomerleau, Post-Doctoral Fellow (University of Manitoba)
Cortney Watt, Post-Doctoral Fellow (University of British Columbia)
Alyysa Bohart, Research Associate (University of Alberta)

Cornelia Willing, Research Associate (University of Manitoba)
Brent Young, Research Associate (University of Manitoba)
Alexandra Beatty, Undergraduate Student (University of Alberta)
Linda Nguyen, Undergraduate Student (University of Alberta)
Meredith Yee, Undergraduate Student (University of Alberta)

Northern HQP

Jeff Amarualik, Northern Research Staff (Hamlet of Resolute Bay)
Peter Amarualik, Northern Research Staff (Hamlet of Resolute Bay)
Uluriak Amarualik, Northern Research Staff (Hamlet of Resolute Bay)
Lucassie Arragutainaq, Northern Research Staff (Hamlet of Sanikiluaq)
Eric Kilabuk, Northern Research Staff (Hamlet of Pangnirtung)
Ricky Kilabuk, Northern Research Staff (Hamlet of Pangnirtung)
Frank Nutarasungnik, Northern Research Staff (Hamlet of Arviat)

ABSTRACT

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

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

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

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

KEY MESSAGES

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

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

OBJECTIVES

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

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

INTRODUCTION

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

Our research builds on data collected during previous ArcticNet funding cycles, and primarily addresses how various aspects of marine mammal demography (population dynamics), distribution, and health are linked with environmental variables, particularly sea ice. We are focusing on Arctic seals (ringed seals, *Pusa hipsida*; bearded seals, *Erignathus barbatus*; and harbor seals, *Phoca vitulina*), whales (beluga, *Delphinapterus leucas*; narwhal, *Monodon monceros*; bowhead whales, *Balaena mysticetus*; and killer whales, *Orcinus orca*), and polar bears (*Urus maritimus*) to answer questions such as: (1) How will marine mammals adapt to global warming – and what are the possibilities for persistence in space and time? (2) What is the relationship between warming temperatures and marine mammal habitats? (3) What are the potential effects of global warming on reproduction and survival? (4) What will be the effects of changes in marine mammal populations on northern communities and Inuit lifestyle? (5) Can non-invasive samples provide early indicators of environmental change? (6) How can we reduce the impacts of these changes on Arctic peoples and marine mammals?

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

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

ACTIVITIES

Seals

Ringed seal studies during 2015-2016 were focused primarily on diet and population/reproduction assessments. Diet studies determined whether ringed seals, as a species, have the capacity to adjust their foraging ecology in a changing environment, which provided insight into the foraging plasticity of arctic biota and their potential to eventually adapt to ecosystem shifts. Genetics studies focused on assessing trends in ringed seal abundance using genetics profiles to estimate effective population size, and to compare temporal trends in abundance with environmental variables such as ice thickness, the timing of spring break-up, spring precipitation, and spring temperature. These variables have previously been shown to affect reproduction and pup survival.

The following activities were completed in 2015-2016:

- Genetic profiles for 500 plus ringed seal samples collected from throughout the Canadian Arctic and Greenland were generated to understand ringed seal population structure and gene flow, as well as the number of breeding seals. This data was added to the existing database of over 1500 samples.
- Harbor seal behavior (e.g. mating) and numbers in the Churchill River estuary was monitored for two weeks to determine their habitat use and abundance.
- Tissues from 36 ringed and bearded seals harvested by local hunters near Arviat were collected during the end of October. Fatty acid analysis procedures for diet analysis of these samples at the Freshwater Institute in Winnipeg were updated.
- Stomach contents from over 50 ringed seals from seven communities throughout the eastern Canadian Arctic were sorted and identified as part of a study examining ringed seal foraging ecology.
- Community based sample collections of ringed seal tissues were performed by hunters from Arviat, Sanikiluaq, Kugaaruk, Resolute, Pond Inlet, Pangnirtung, and Gjoa Haven. In addition, through collaboration with the Government of Nunavut Fisheries and Sealing Division and the Wildlife Officers stationed in communities, samples from ringed seal pelts were obtained from Kimmirut, Pond Inlet, Arctic Bay, Pangnirtung, and Sanikiluaq.
- A project examining growth layer groups (GLGs) in ringed seal tooth cementum was initiated in 2015. GLG widths in teeth of seals from Arviat and Sanikiluaq have been measured and will be analysed to determine whether patterns in seal growth over time are related to local environmental conditions or to global climate patterns.
- Ringed seal liver (~1200) and muscle (~1100) samples from across the Arctic were analysed for stable isotopes.
- Ringed seal satellite telemetry data from Resolute (n=7), Ulukhaktok (n=25), Igloolik (n=7), Sanikiluaq (n=80), Saglek Bay (n=13) and in Melville Bay, Greenland (n=13) was analysed.

Whales

Studies on arctic whales (narwhals, belugas, bowhead whales, and killer whales) in 2015-2016 focused on identifying foraging habitat characteristics, as well as assessing diet shifts associated with shifts in their prey base. Narwhal studies focused on evaluating critical foraging areas of the Baffin Bay and Northern Hudson Bay populations, while beluga studies focused on long-term diet shifts (fatty acid profiles of tissues collected from the 1970s to 2010) and seasonal foraging behavior (from dive profiles of satellite-tagged animals) of the Cumberland Sound population. Bowhead studies also focused on Cumberland Sound, where goals were to assess foraging behavior from dive profiles, and to conduct detailed characterizations of zooplankton distribution and composition in areas where bowhead whales were feeding. Additional research on bowhead whales off western Greenland used compound specific stable isotope analysis to understand how bowhead whale diet varies with year-to-year differences in sea ice. Killer whale research was based out of Admiralty Inlet on northern Baffin Island, where goals were to satellite tag, biopsy, and photograph animals to learn more about diet, distribution and movements, and population structure.

The following activities were completed in 2015-2016:

- Narwhal satellite telemetry data was analysed to determine winter habitat selection in southern Baffin Bay/northern Davis Strait, focusing on ice concentration, ice thickness, ice floe size, bathymetry, and distance to shore as important variables.

- An aerial survey of beluga whales was conducted in western Hudson Bay. The survey consisted of photographic and visual surveys in the high density areas of the Churchill, Seal, and Nelson Rivers, as well as high density areas along the coast, and low density areas off-shore.
- Nine beluga whales were captured and attached with satellite transmitters in the Churchill estuary, Hudson Bay. Telemetry results will be combined with past projects from the Seal River, Nelson River, Nastopoka River, and James Bay estuaries to understand fidelity to estuary use in summer, migration patterns, and winter range, as well as using dive behaviour to determine foraging habits.
- Bulk and compound specific (amino acid) stable isotope analysis was performed on bowhead whale skin samples collected in Disko Bay.
- Narwhal satellite tracking data were analysed to determine where deep diving was occurring, and home range analyses were run to get an estimate of the areas used for foraging in the summer, winter, and migration season for narwhals from Baffin Bay and Northern Hudson Bay.
- Cumberland Sound beluga blubber and liver samples from the 1980s-2010 were analyzed for fatty acids and highly-branched isoprenoids, respectively, to determine if diet has changed over time. Dive data was analyzed to determine if foraging behaviour varies across seasons.
- Narwhal and beluga reproductive tracts collected by Inuit hunters were dissected and examined for typical/atypical anatomy of the reproductive organs. Male reproductive assessment included baculum length and testis length and mass. Female assessment included uterine horn length, ovary weight and dimension, and fetal measurements, if present.
- Bowhead work in Cumberland Sound (i.e. tagging and biopsying) was unsuccessful due to unusual and extreme ice conditions that persisted throughout the entire summer in Cumberland Sound. However, zooplankton were collected from Pangnirtung Fiord near the ice-edge to quantify abundance and community structure, and to determine the energetic content of zooplankton and the life history of the sampled organisms.
- Fieldwork to satellite tag and biopsy killer whales in Admiralty Inlet was largely delayed due to weather. However, on the last day of fieldwork, killer whales previously encountered in 2009 were observed and identified from photographs taken by the research team.

Polar bears

Polar bear research in 2015-2016 was related to identification of biomarkers that will allow early detection of population changes in response to climate change. We focused on developing interdisciplinary means of assessing life history events from microanalysis of hard tissues and other relevant tissues (e.g., hair, blood, teeth) in several populations of polar bears: the Southern Beaufort Sea, Western Hudson Bay, Foxe Basin, and High Arctic.

The following tasks were completed in 2015-2016:

- Archived samples from polar bears in several populations across Canada collected over the past 20 years were analysed for stable isotopes and stress hormone (cortisol) concentration to determine whether polar bear health is impacted by long-term physiological stress associated with climate change.
- Cortisol, the principal effector hormone of the stress response, was measured in hair samples from 729 polar bears from Western Hudson Bay sampled from 2004 - 2013. The influence of age, reproductive status, and body condition (fatness) on hair cortisol levels were examined.
- Stable carbon and nitrogen isotope analysis of 400 polar bear hair samples from western Hudson Bay were completed. Pending statistical analysis of these samples, priorities for additional

sampling of archived material will be determined. Additional projects pending for similar analyses include the Beaufort Sea and Baffin Bay.

- A database of relevant sea ice metrics for use in the analysis of our biomarker data has been established. These analyses are ongoing and will form the basis of several new publications.

RESULTS

Many of the activities in 2015 were undertaken by new graduate students whose programs are in early stages, and therefore, results and interpretations are not expected until the upcoming year. Important results from studies of seal and whale foraging ecology, as well as initial results from polar bear tissue examination, are outlined below.

Seals

Stable isotopes showed an ontogenetic niche shift, with adults having a more restricted niche than subadults, which was due to higher consumption of forage fish by adults. A general latitudinal trend existed where the level of fish consumption and trophic position of ringed seals decreased due to increased prevalence of sub-arctic fish species and less trophic complexity in the zooplankton community at lower latitudes. Isotopic niche size for ringed seals and beluga whales (*Delphinapterus leucas*) increased at lower latitudes and level of individual specialization in ringed seals increased at lower latitudes, likely as a response to large-scale spatial variation in ecological opportunity (i.e. prey species richness) which is higher at lower latitudes (Figure 1).

Satellite telemetry also revealed important latitudinal differences in ringed seal ecology, as individuals from higher latitudes spend more time traveling and less time foraging than individuals from lower latitudes, where inter-annual sea dynamics were less variable. Also, smaller individuals also spend more time transiting between habitat patches than their larger conspecifics due to competitive exclusion (Figure 2).

Genetics analysis of ringed seal tissues indicated that there is no significant temporal trend in effective population size or effective number of breeders in the Western Hudson Bay populations of ringed seals (Figure 3; note, however, the large confidence intervals for these estimates). In 2014, we observed the highest abundance of harbour seals recorded in the Churchill River estuary (Figure 4). An increase in population abundance of harbour seals in the Churchill River estuary in 2014 and 2015 was noted relative to previous 2005 estimates from Bernhardt (2006), and the first instances of pupping and possible breeding activity (adults with blood on their pelts) in the estuary were recorded. Surveys in 1998-2000 and 2005 indicated that pupping occurs outside of the estuary (Bajzak et al. 2013), which suggests that the pupping location has changed over the past two decades.

Whales

Home range analyses of narwhal telemetry data revealed important areas for foraging on both the summer and winter grounds, as well as on the migratory pathway between the areas for animals from the Baffin Bay and Northern Hudson Bay populations, suggesting at least some foraging occurs year-round.

For Cumberland Sound beluga, a change in the fatty acid profile of blubber was noted from the 1980s compared to the 1990s and 2000s (Figure 5). Specific fatty acids indicative of capelin and Arctic cod showed increasing and decreasing trends over time respectively, suggesting an increased consumption of capelin with a reduction in Arctic cod in summer in more recent years. Dive behaviour suggested different foraging tactics across seasons. Shallow short dives occurred in summer, which may indicate foraging on capelin, while deeper longer dives were made in autumn and winter, indicating foraging on deeper prey such as Arctic cod and Greenland halibut.

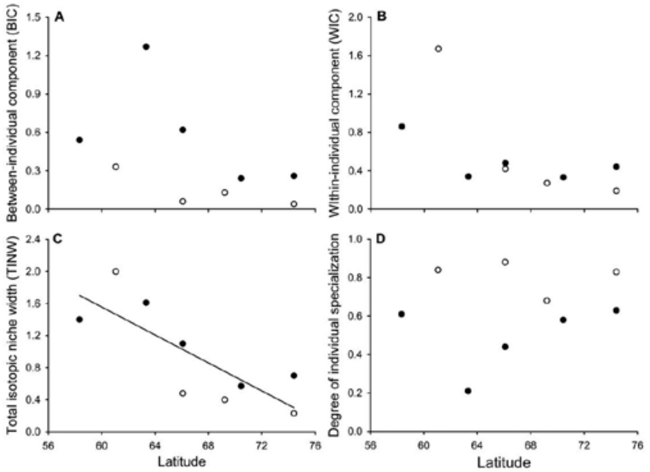

Figure 1. Linear regressions of (A) between-individual component (BIC), (B) within-individual component (WIC), (C) total isotopic niche width (TINW) and (D) degree of individual specialization (WIC/TINW) for combined ringed seals (closed circles) and beluga whales (open circles) relative to latitude. A significant relationship only occurred between TINW and latitude when both species were analyzed together. No significant relationships between each niche metric and latitude occurred when species were analyzed separately.

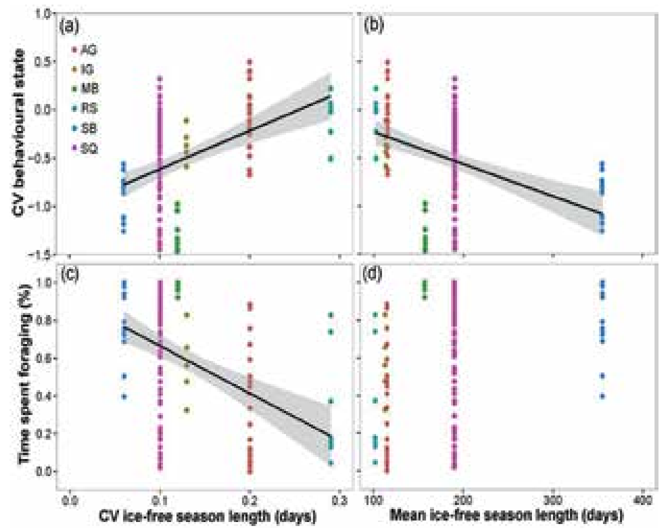

Figure 2. Relationships of coefficient of variation (CV) of behavioural state and time spent foraging (%) for all ringed seal individuals by location relative to CV of ice-free season length (a, c) and mean ice-free season length (b, d). Linear regression lines are only provided for statistically significant relationships where the gray band represents the 95% confidence interval. The legend in panel (a) corresponds to all other panels. AG: Amundsen Gulf; IG: Igloolik; MB: Melville Bay; RS: Resolute; SB: Saglek Bay; SQ: Sanikiluaq.

Zooplankton sampling in Cumberland Sound indicated the greatest abundances of zooplankton were found in the surface waters (10-20 m) and near the sea bottom (60-80 m) (Figure 6), which contrasts with findings from August 2014 when maximum zooplankton densities occurred only at depth. Preliminary insights suggest that the zooplankton samples consist primarily of early-staged calanoid copepods with low abundances of adult female *Calanus hyperboreus*. Given the persistence of sea ice throughout Cumberland Sound and at the mouth of Pangnirtung Fiord, it is anticipated that the phytoplankton bloom would be delayed. Phytoplankton blooms are light dependent and given the delayed ice break-up this summer, it is not surprising that maximum zooplankton densities appear to occur near the thermocline (likely close to the mixed layer at ~10 m; Figure 7) throughout August. Furthermore, the adult female *Calanus hyperboreus* appeared to have

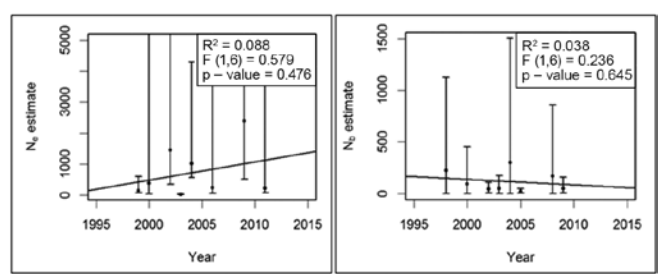

Figure 3. Linear regression of genetic parameters related to abundance showed no significant trends over time. Although the regression line for estimates of effective population size (Ne) is positive and the regression line for effective number of breeders (Nb) is negative, the confidence intervals are large and neither show significant a relationship between the dependent variable and time.

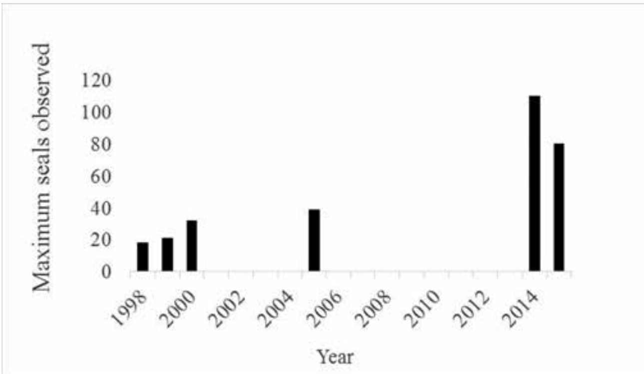

Figure 4. Maximum number of harbour seals observed in the Churchill River estuary from 1998-2015. Years with no seals were years no observations were made. Data from 1998-2005 from Bernhardt (2006).

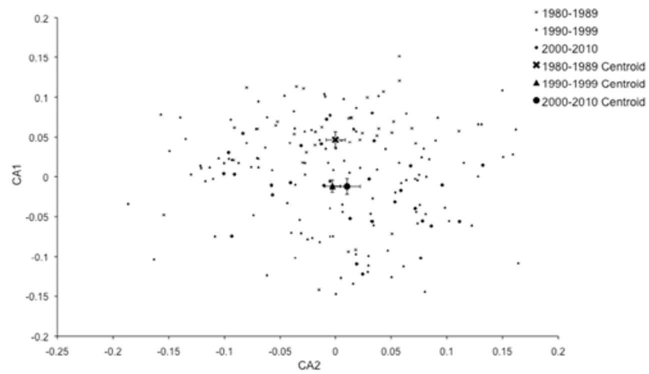

Figure 5. Canonical plot of beluga fatty acids from three time periods (1980-1989 (number of whales sampled = 38), 1990-1999 (n = 119), and 2000-2010 (n = 31)). Centroids ± SE are plotted for each time period.

foraged recently (green pigment in gut) suggesting that organisms collected from the surface waters were feeding on phytoplankton.

Bulk $\delta^{15}N$ values of bowhead whale skin were consistent across the seven years of sampling and were similar between sex classes, while bulk $\delta^{13}C$ and average essential AAs $\delta^{13}C$ values displayed a small but significant temporal decreased between 2008 and 2013. Despite large interannual variations in sea-ice cover, no significant correlations were found between bulk, $\delta^{13}C$-AAs or $\delta^{15}N$-AAs isotopic signatures and sea ice concentrations, indicating that the trophic position of bowhead whales was stable over time despite large inter-annual variability in sea-ice cover.

Polar Bears

Overall, there was a negative relationship between fatness and cortisol levels in polar bears, suggesting that bears in poorer body condition experienced higher levels of stress. However, when reproductive status was included in our analysis, this relationship only held for male and lone female bears. Females with dependent offspring had consistently low fatness and elevated cortisol, likely because of the high cost of maternal care. A positive correlation between HCC and age occurred in bears in: 1) poorer body condition, possibly due to nutritional stress compounding effects of senescence; and 2) male bears, potentially due to stress and injury associated with intrasexual mate competition. These findings support the use of hair cortisol as a biomarker for polar bear health. Furthermore, we have established a HCC benchmark against which future effects of continued climate change on polar bear health can be measured.

DISCUSSION

Seals

Stable isotope results revealed that ringed seals are responding to large-scale spatial differences in the availability and distribution of native and non-native prey species between the high- and low-Arctic, suggesting plasticity in their foraging decisions and differences in food web structure across the Arctic. The increase in adult isotopic niche size over time is likely in response to recent circumpolar increases in subarctic forage fish distribution and abundance. The high degree of dietary plasticity and interannual variation in ringed seal diet suggest adaptability in terms of their diet to climate change. However, long-term monitoring of ringed biological parameters (such as body condition indices), which have declined over time in some areas of the Arctic (Harwood et al. 2015), is required

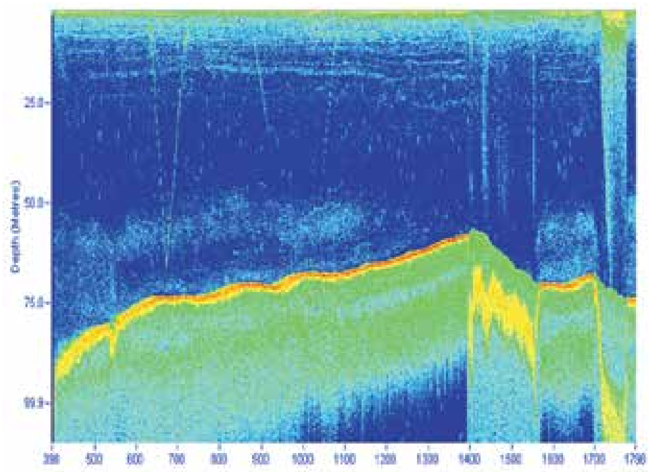

Figure 6. Example of an echogram collected from the multi-frequency echosounder (AZFP) at 125 kHz. It appears as though there are zooplankton aggregations near the surface and above the seafloor in Pangnirtung Fiord during August. Also apparent are two distinct v-shaped objects, which capture two OPC and CTD cage deployments.

in order to gain more insight into Arctic ecosystem dynamics in our rapidly changing climate.

Ringed seals are a particularly difficult species to assess abundance, due to their cryptic behaviour, large distribution, and high abundance. This holds true for assessment through the use of genetic parameters, or at least effective population size. The genetic drift method for estimating effective population size is more accurate when samples from many generations exist. The generation length for ringed seals is 11 years, which means that for practical purposes our dataset spans a maximum of two generations. An alternative method of estimating contemporary effective population size, also known as inbreeding effective population size, has the advantage of only requiring samples from one time period or generation to estimate effective population size. However, these estimators require relatively large sample sizes and many loci to yield precise estimates of effective population size or effective number of breeders. Development of these estimators is ongoing and they are improving rapidly. Also, with the increased use of single nucleotide polymorphisms new estimators are being developed that may be better suited to this species. We are currently adding samples and loci and testing other estimators to see if more clear results can be obtained. As estimating abundance for ringed seals is an ongoing problem, we hope that our work will inform future data collection and co-management strategies.

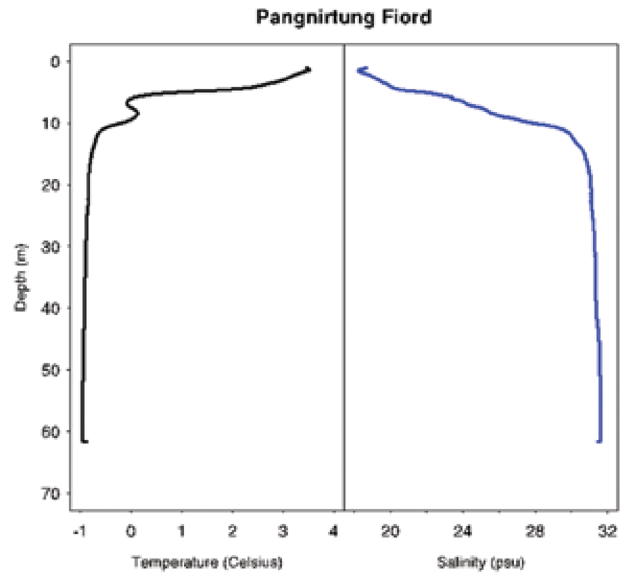

Figure 7. Example of temperature and salinity plot collected on 13 August in Pangnirtung Fiord using the seabird SBE19Plus CTD. Stratified waters consisted of fresher and warmer water at the surface (0-10 m) and colder and saltier water at depth (>15 m), which is common for a fiord system during summer.

Although the cause of the increase in harbour seal abundance in the Churchill River estuary is not understood, changes in environmental conditions may have allowed for population growth. It is possible that the river is becoming ice-free sooner and allowing pupping to occur on land in the estuary as opposed to on ice or at unknown alternative locations. This shift may increase survival and lead to the higher abundance observed and may suggest that this population is growing. Monitoring of the population dynamics of harbour seals in the Churchill River is ongoing.

Whales

The narwhal study is the first to identify key areas used by narwhals for foraging, which is vital for understanding the species' habitat requirements, for determining the impacts of anthropogenic activities on narwhal populations, and for developing conservation areas. Narwhals forage on their summer and winter grounds, as well as on the migration between the two regions, which may make them vulnerable to increases in anthropogenic activities. The migratory season is an important time for benthic foraging, and industrial activities at this time may deter foraging, or change the directional movements of the animals, which in turn may prevent them from reaching their summering or wintering areas or reduce critical energy intake. By determining important areas for narwhal foraging we are better able to predict and mitigate the impacts of increasing anthropogenic disturbances in the Arctic.

Beluga whales seem to have adjusted their foraging behaviour from the 1980s to 2010 to adapt to an increased abundance of capelin in Cumberland Sound. The change from a summer diet reliant on cod to one dominated by capelin may not be a conservation concern since belugas in other regions also rely heavily on capelin to meet their dietary requirements. However, deep diving by belugas in Cumberland Sound suggests winter is an important season for amassing energy reserves and this may be a conservation concern since it will create a competitive conflict for resource use between belugas and expanding commercial fisheries. An understanding of beluga seasonal and spatial habitat use, diet, and dive behaviour is needed to make informed conservation targets for the threatened Cumberland Sound beluga population. Our study highlights that food web changes are currently being reflected in beluga diet and winter foraging may be particularly vital for the species.

Initial results from compound specific stable isotope analysis that show bowhead whale diet to be relatively stable despite strong interannual variation in the amount and timing of sea ice suggests at least short term environmental variation may have little impact on their ability to meet energetic requirements.

Polar bears

Development of early warning systems for wildlife remains a priority for managers of natural resources. Our project is focused 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. Specifically, to understand how the levels of a biomarker are responding to climate change, we need to have a fundamental understanding of the role of sex, age, reproductive status, and date of sampling. The project priorities in 2015 were to establish this baseline information. Ongoing analyses will now move towards more refined insights and developing linkages to sea ice and climatic parameters. Less invasive methods are a priority for northern communities and our research will make meaningful contributions.

CONCLUSION

In conclusion, with respect to marine mammal health, Arctic marine food webs are under immense pressure from a variety of factors including global pollution, hydrocarbon exploration and production, commercial fisheries, and climate change. Complex spatial-temporal shifts in ecological and subsequently demographic constraints are ongoing, that suggest that the arctic marine ecosystem is undergoing changes as a whole. It is to be expected that this trend will continue in light of the current and future Arctic climatic alterations and the continued and increasing presence of anthropogenic influences in the Arctic. With a changing Arctic ecosystem, the ecology of marine mammals adapted to sea ice habitat as an integral part of the ecosystem will also be affected. Altered population dynamics, abundance trends, migration patterns and new prey and predators are likely results.

Expansion of ecological/biological investigations and wildlife health biomedical baseline studies, concurrent to already established demographic research on distribution and abundance for local management, and subsistence foods monitoring programs are therefore key to conservation success. The "Innovative Research on Monitoring Marine Mammals to Mitigate Impacts of a Changing Arctic" marine mammal research group plans to use the final two years of funding through ArcticNet centre of excellence to complete a final synthesis effort to bring to conclusion the ongoing long-term studies.

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The Arctic Cod (*Boreogadus saida*) Ecosystem of the Beaufort Sea: Synthesis of Decadal Records

Project Leader

Louis Fortier (Université Laval)

Collaborators

Marcel Babin (Université Laval)
Alexandre Forest (Université Laval)
Catherine Lalande (Université Laval)
Frédéric Maps (Université Laval)
Eva-Maria Nöthig (Alfred-Wegener Institute Helmholtz Centre for Polar and Marine Research)
Dominique Robert (Québec-Océan)
Makoto Sampei (Université Laval)
Yvan Simard (Université du Québec à Rimouski)

HQP

Maxime Geoffroy, Doctoral Student (Université Laval)
Acoustic signature, distribution, and abundance of pelagic fish and marine mammals in the Canadian Beaufort Sea (Arctic Ocean)
Jordan Grigor, Doctoral Student (Québec-Océan)
The ecologies and physiologies of arrow worms in the Arctic
Sarah Schembri, Doctoral Student (Université Laval)
Moritz Schmid, Doctoral Student (Université Laval)
Spatiotemporal Variability In The Mesozooplankton – Primary Production Coupling Using Optical Imaging Systems
Thibaud Dezutter, Masters Student (Université Laval)
Mathieu Leblanc, Masters Student (Université du Québec à Rimouski)
Cyril Aubry, Technical Staff (Université Laval)

ABSTRACT

Except during overwintering expeditions, the Beaufort Sea and the Arctic Ocean Basin per se are reachable by the Amundsen research icebreaker only from late summer until the end of October. Hence, most of the annual cycle of the ecosystem including the pivotal early summer productive season and the long winter-spring overwintering season is cloaked from direct observation. Our best tool to monitor interannual variability and potential climate-linked trends in key indicators of ecosystem function are the sequential traps deployed since 2002 on CASES and then ArcticNet oceanographic moorings. The moorings consist in lines of recording instruments anchored on the seafloor and maintained at different depths in the water above by floats. The instruments record the speed and direction of currents, the salinity, temperature, and nutrient content of the water, the abundance of chlorophyll (a pigment proportional to microalgal abundance), and ambient noise including the vocalizations of marine mammals. In addition, some moorings carry sediment traps, which are large automated funnels that intercept and bottle at regular intervals the plankton particles raining from the surface layer of the ocean. Such particles include ice algae, phytoplankton (vegetal cells), zooplankton (planktonic animals), zooplankton fecal pellets and all sorts of detritus, which are all excellent indicators of the intensity of different ecosystem processes taking place in the surface ocean. The most complete series available are for the slope of the Beaufort Sea, a region of ecological importance targeted for oil exploration. In close collaboration with the Long-Term Oceanic Observatories (LTOO) and the integrated Beaufort Observatory (iBO), the Arctic Cod project will maintain this series until 2018 and will exploit existing sequential sediment trap records to detect interannual variations and change in the annual cycle of the ecosystem. In particular, we will focus on changes from year to year in the timing and intensity of the annual cycle of abundance of large calanoid copepods (the main grazers of microalgae and important food for Arctic cod) and the nauplii of copepods which are the main prey of the larval and juvenile stages of Arctic cod from late winter to summer. Our objective is to recapitulate variations in this 16-year record to detect any response of the ecosystem to recent changes in the Beaufort Sea environment. If such a response was detected, it likely would represent the very first symptom of a shift of the Arctic pelagic food web towards a more boreal food web, with all the expected modifications in the services (e.g. food, health, revenues, skins, cultural bonding, etc.) provided to local communities by the present ecosystem.

KEY MESSAGES

- In the Beaufort Sea, interannual variations in the size and abundance of epipelagic juvenile Arctic cod in early fall are linked to the date of the ice break-up and summer sea surface temperatures (SSTs). An early break-up and a warm surface layer result in large and abundant juveniles. Interannual differences in size at age are too large to be explained by temperature-forced differences in growth. They rather result from earlier-hatched (and hence larger in the fall) larvae surviving in years of early ice break-up.
- Over the annual cycle, epipelagic (0-100 m layer) young-of-the-year Arctic cod are separated from their mesopelagic (200-500 m layer) cannibalistic adult congeners. Changes in ice-cover and the temperature of the surface layer due to climate as well as a surface oil spill will affect the epipelagic larvae and juveniles. A deep spill spreading isopycnally would impact the mesopelagic adults.
- The first results of our analysis of zooplankton “swimmers” collected in sediment traps over six annual cycles from 2003 to 2015 indicate large interannual differences in the timing and abundance of major preys of larval and juvenile Arctic cod (copepod nauplii, appendicularians,

Oithona similis), that could be related to interannual variations in sea-ice regime.

- Interestingly, the series demonstrate the emergence of copepod nauplii under the ice as early as January and February in some years, a result that explains the otherwise puzzling hatching of Arctic cod larvae starting as early as January in the region.
- The IRIS 1 (Western High Arctic) stressed the lack of sufficient information on the marine ecosystems of the Kitikmeot and recommended increased research efforts in the region. A synthesis of prior information and new results from the Victoria-Strait-Queen-Maud-Gulf research partnership with Parks Canada funded by the W. Garfield Weston Foundation identifies the region as an important ecological transition zone between the Western Arctic and the Eastern Arctic.
- Additional progress in the automated computer identification of the images provided by the Lightframe On-sight Keyspecies Investigation System (LOKI) provides a 1-m resolution of the vertical distribution of zooplankton, allowing unprecedented analysis of the co-distribution of key copepods such as *Calanus hyperboreus, C. glacialis* and *Metridia longa* and their phytoplankton food.
- The common and similar arctic chaetognaths *Eukrohnia hamata* and *Parasagitta elegans* partition resources by evolving different reproductive strategies. The income-breeder epipelagic *P. elegans* reproduces from summer to early winter, when copepod prey peak. The capital-breeder mesopelagic *E. hamata* stores lipids to fuel the production of distinct broods in spring-summer and winter.
- The SX90 fisheries sonar is a useful complement to direct observations for the detection of marine mammals in low visibility and darkness. The sonar can also be used for the mapping of icebergs.

OBJECTIVES

1. Describe interannual variations (2002-2018) in the absolute and relative abundance of the prey (e.g. copepod nauplii, early copepodites, *Oithona similis*) and potential predators (chaetognaths, the predatory copepod *Euchaeta glacialis* and the hyperiid amphipod *Themisto libellulla*) of fish larvae collected by sediment traps in the Beaufort Sea;
2. Relate interannual variations in the hatching season (an index of seasonal survival) and early growth of larval and juvenile Arctic cod in the Beaufort Sea to zooplankton prey abundance indices (e.g. nauplii abundance) from sediment trap records;
3. Correlate interannual variations in the acoustically-derived abundance and size of juvenile Arctic cod in the fall to variations in sea ice cover, surface temperature, and zooplankton prey abundance indices (e.g. nauplii abundance) from sediment trap records in the Beaufort Sea and in other regions of the Canadian Arctic Ocean;
4. Document the fine-scale vertical distribution and migration of the arctic calanoid copepods *Calanus glacialis* and *C. hyperboreus* in relation to the phytoplankton bloom using the new LOKI in-situ image profiler;
5. Complete our studies of the ecology of the common chaetognaths *Eukrohnia hamata* and *Parasagitta elegans* in the Beaufort Sea;
6. Pursue our description of the Kitikmeot marine ecosystems in response to the recommendation of the IRIS 1.

INTRODUCTION

The pelagic ecosystem of the Arctic Ocean supplies local communities with many goods and services that include traditional food (fish, marine mammals and birds), "traditional" health (omega-3, selenium, etc.), furs and leather, heating oil, substrates for sculpture (e.g. bones and ivory), inspiration for the arts, social cohesion, intergenerational bonding, spiritual comfort, and life fulfilling. As the sea-ice cover of Arctic seas shrinks and their surface layer warms up, signs of the expected replacement of the unique Arctic pelagic ecosystem by North-Atlantic and North-Pacific ecosystem types are increasingly detected (e.g. Tynan and Demaster 1997; Gaston et al. 2003; Grebmeier et al. 2006; Falardeau et al. 2014). The atlantification/pacification of the Arctic pelagic ecosystem threatens the services rendered to northern communities, and harbingers a shift to different ecosystem services that will benefit primarily southern industries: for instance, access to oil and other mineral resources, new shipping lanes, fish stocks of commercial interest, and ecotourism.

The objective of ArcticNet IRISes is to provide Inuit communities, the private sector, and governments with the relevant scientific information to formulate the policies, adaptation strategies, and decisions that will shape the response of Canada to climate change and modernization in the Arctic. As far as marine ecosystem services are concerned, anticipating the rate and timing of the expected transformation of the pelagic Arctic ecosystem is a crucial element of all four IRISes. The Arctic cod (*Boreogadus saida*) is a key component of the relatively simple Arctic Ocean pelagic ecosystem. This small forage fish channels up to 75% of the energy transfer between the plankton and the fish, seals, whales and marine birds that supply many ecosystem services (Welch et al. 1992). A hyper-specialist adapted to life in ice-covered seas, Arctic cod is likely to be rapidly displaced by southern generalists as the ice regime becomes less severe. In northern Hudson Bay where ice decline is intense, capelin and sand lance have replaced Arctic cod as the main prey brought back to the nest by thick-billed murres to feed their young (Gaston et al. 2003). Similarly, in the Beaufort Sea where ice retreat is also severe, our own studies of the ichthyoplankton assemblage indicate the recent intrusion of the Pacific sand lance in the offshore distribution area of juvenile Arctic cod (Falardeau et al. 2014). We believe that changes in the ecology of Arctic cod, including its displacement by boreal forage fishes, are likely among the most powerful indicators of the transition of the Arctic Ocean pelagic ecosystem to a new equilibrium.

As part of the CASES program and then the annual ArcticNet mission, every year since 2002 (with the exception of 2013) we have mapped by acoustics the fall distribution of Arctic cod in the Beaufort Sea, reconstructed its hatching season and early growth based on the analysis of the otoliths of juveniles captured in the fall, and monitored changes in the ichthyoplankton assemblage to which it belongs. All these variables have been measured over several weeks in early fall, at the end of the short productive season during the annual mission of the CCGS *Amundsen* (or CCGS *Radisson* in 2002) to the region. For reasons independent of our control, the dates of arrival and departure of the icebreaker in the Beaufort Sea, and hence the sampling period, varied considerably from year to year over the period 2002-2014. These differences in sampling dates combine to natural variations in the phenology of the ecosystem to make the interannual comparison of other key variables difficult. For example, differences between years in the availability of zooplankton prey to juvenile Arctic cod at the time of sampling in the fall may reflect differences in sampling dates as well as interannual differences in the intensity and/or timing of the production of copepods which are the main prey of the young fish. As well, except for the overwintering expeditions of 2003-2004 and 2007-2008, we have no direct information on the survival conditions (e.g. the abundance of prey and predators) in late spring and early summer during the larval and early juvenile life of Arctic cod in the plankton. However, recent work by our international team indicates that the abundance and condition of zooplankton collected over the annual cycle by moored sequential sediment traps (a.k.a. "swimmers") can provide precious indirect information on food availability and predation pressure for the planktonic stages of Arctic cod and on food availability to the adult stages living on the shelf slope (Makabe et al., 2010; Makabe et al., submitted to Polar

Biology). As well, the marine mammal vocalizations recorded by passive acoustics hydrophones moored on the same lines (e.g. Kinda et al. 2013) provide indications on the abundance of the predators of adult Arctic cod.

The overarching objective of Arctic cod project is to explore interannual variations and decadal trends (2002-2018) in key indices of Arctic cod ecology and to correlate these to environmental trends so as to detect any response to recent ocean climate variability.

ACTIVITIES

Sampling at sea for Arctic cod was conducted as part of the ArcticNet 2015 mission of the CCGS *Amundsen* to Baffin Bay, the Canadian Arctic Archipelago and the Beaufort Sea. Our sampling program was interrupted and curtailed by the rerouting of the ship to Hudson Bay for 18 days to assist with the sealift for communities. We nevertheless conducted part of the planned sampling of zooplankton, fish larvae and juveniles and adult fish in all targeted areas. The active acoustic program along the track of the ship was successfully completed. To maintain the time series of swimmer collection, moorings carrying sediment traps were deployed in the Beaufort Sea in close collaboration with the Long-Term Oceanographic Observatories (LTOO) program of ArcticNet.

Our team participated in the GreenEdge ice camp deployment off Qikiqtarjuaq from April to June, deploying the LOKI system through the ice for the determination of the fine-scale vertical distribution of zooplankton in relation to the ice and under-ice availability of microalgal food.

The summer of 2015 saw the publication of ArcticNet's IRIS 1 for the Western High Arctic. Our team led the charge for Chapter 4 that covers the marine ecosystems and contaminants (Fortier et al. 2015). An important conclusion of the IRIS 1 is that the marine waters of the Kitikmeot in the Canadian Archipelago were understudied.

In addition to the research program proposed for Arctic cod, we developed in 2015 a new collaboration with Parks Canada funded by the W. Garfield Weston Foundation to document the marine ecosystems of the Kitikmeot region in the Canadian Archipelago (Victoria Strait and Queen Maud Gulf). This new collaboration was motivated by the discovery in the eastern QMG of HMS *Erebus*, one of the two lost ships of the 1848 Franklin expedition, as well as by the conclusion in ArcticNet's IRIS 1 that the ecosystems of the region were understudied. A pilot program was conducted in 2015 comprising additional sampling from the *Amundsen* in VS and QMG, the deployment of one oceanographic mooring in QMG (in collaboration with the LTOO project), as well as some sampling of benthos at the *Erebus* site in collaboration with the team of Archambault.

The Arctic Cod team also participated in the ArcticNet-Statoil Canada partnership to investigate the marine ecosystems of the Labrador Sea, contributing the survey of marine mammals and the mapping of icebergs using the SX90 fisheries sonar, and the production of a report (Geoffroy et al. 2015).

RESULTS

The year 2015-2016 saw the transition from our former ArcticNet project to this new project focused on the retrospective analysis of the accumulated time series since 2002. Hence this report presents results from previous objectives and, although the retrospective analysis of the time-series is only beginning, some results relevant to our new objectives.

Compared ecology of two similar and abundant chaetognaths in the Beaufort Sea

In Arctic seas, primary production and the availability of food to the zooplankton are strongly pulsed between the short productive summer and the long winter. We tested the hypothesis that the similar and common arctic chaetognaths *Eukrohnia hamata* and *Parasagitta elegans* partition resources through different reproductive strategies. Based on seasonal changes in the abundances of newborns (2-4mm long), the epipelagic *P. elegans* reproduces continuously from summer to early winter, when copepod prey peak in near-surface waters, characteristic of income breeders. The mesopelagic *E. hamata* birthed distinct, traceable broods during separate reproductive windows in spring-summer and winter, characteristic of capital breeders. Changes in the length of chaetognaths in successive cohorts over the year suggested that the two species (which have similar natural longevities around two years) grew quickly in spring and summer, but *E. hamata* only kept growing in winter. Storage reserves, contained within its oil vacuole, allow *E. hamata* to reproduce and grow outside the short production season in the Arctic (Figure 1).

Automatic in situ identification of arctic zooplankton

The Lightframe On-sight Keyspecies Investigation (LOKI) profiler concentrates the plankton into a photographic chamber to provide clear *in situ* images of mesozooplankton organisms over a profile of the water column. In 2015-2016 we perfected an automatic identification model based on the machine learning algorithm Random Forests, which identifies organisms and the copepodite stages of the main copepods in the LOKI images. The model successfully distinguished between 114 different plankton and particle categories, including the copepodite stages of copepods in different orientations. For two test deployments, the zooplankton going through the LOKI system was recuperated in a cod-end (Figure 2).

Validation of the computer identification against the actual taxonomical composition confirmed the overall accuracy (86%) and specificity (86%) of the model. The taxonomist and the computer were in particularly good agreement for the dominant *Calanus hyperboreus*, *C. glacialis* and *Metridia longa*. The combined vertical resolution of the profile (in the order of one meter) and automatic identification system opens new avenues for the study of arctic zooplankton dynamics in relation to the phytoplankton and other trophic levels (Figure 3).

The SX90 fisheries sonar as a tool to detect and avoid marine mammals

Active acoustics as a tool to detect and avoid arctic marine mammals was assessed in the Canadian Beaufort Sea. The target strengths and shape of the echoes of whales and seals were characterized using a bi-frequency (38 and 120 kHz) split-beam scientific

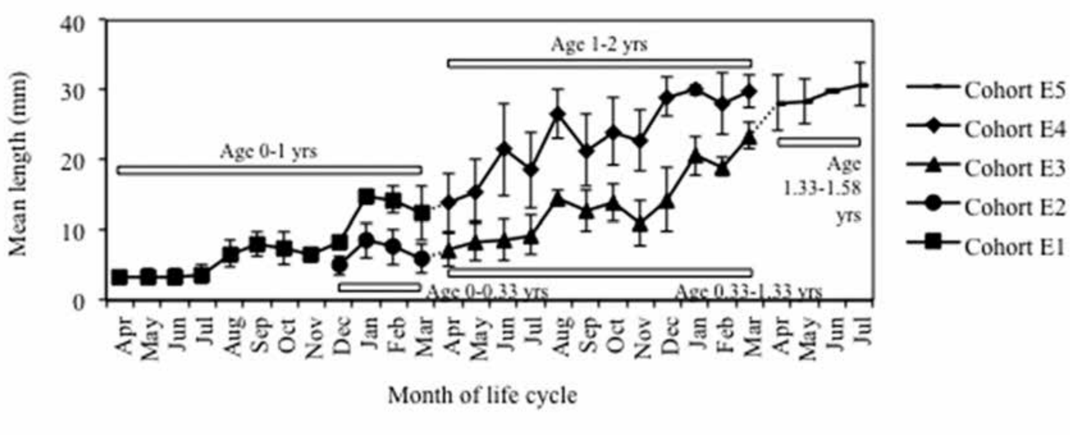

Figure 1. Eukrohnia. hamata brood development curves inferred from individual cohort monthly size-frequency distributions. Cohorts E1 (squares) and E4 (diamonds) represent different ages of spring brood individuals. Cohorts E2 (circles), E3 (triangles) and E5 (dashes) represent different ages of winter brood individuals. Dashed lines link cohorts.

Figure 2. The LOKI in situ zooplankton imager (left) and its deployment from the Amundsen as a component of the zooplankton multiple-net vertical sampler (right).

echosounder in winter 2003-2004 and a scientific scanning sonar (20 to 30 kHz) in summer 2011. The echosounder detected 452 signals of diving ringed seals and the sonar detected 59 bowhead whales, 13 ringed seals and 2 bearded seals. Target strengths of diving ringed seals tracked by the echosounder ranged from -56 to -12 dB re: 1 m^2 and did not vary with the depth of the animal. Target strengths of animals tracked by the sonar varied from -15 to 10 dB for bowhead whales and from -37 to -3 dB for seals. Marine mammals presented higher target strength values near broadside than near tail- or head-on. The sonar detected whales at a distance up to 2000 m and their echoes were discriminated from that of seals. This study suggests that active acoustic technology can be used as a complementary tool for marine mammal surveys in the Arctic.

Vertical segregation of age-0 and age-1+ polar cod over the annual cycle

Hydroacoustic records from 2006 to 2012 were analysed to test the hypothesis that age-0 polar cod segregate vertically from larger congeners. Trawls and ichthyoplankton nets validated the acoustic signal. Fish length, weight, and biomass were estimated from new regressions of target strength and weight on standard length. Polar cod were vertically segregated by size in all months, with small age-0 juveniles in the epipelagic (<100 m) layer and larger age-1+ deeper in the water column. From December to March, the biomass of age-1+ peaked in a mesopelagic layer between 200 and 400 m. With increasing irradiance from April to July, the mesopelagic layer deepened and extended to 600 m. Starting in July, age-0 polar cod formed an epipelagic scattering layer that persisted until November. From September onward, age-0 left the epipelagic layer to join small age-1+ in the upper mesopelagic layer. Low biomass in the mesopelagic layer from February to September likely resulted from large polar cod settling on the seafloor to avoid diving marine mammals. Longer ice-free seasons, warmer sea-surface temperatures, or an oil spill at the surface would likely impact epipelagic age-0, while mesopelagic age-1+ would be vulnerable to an eventual oil plume spreading over and above the seafloor. Published in November 2015, this study has already reached 100 reads according to ResearchGate (Figure 4).

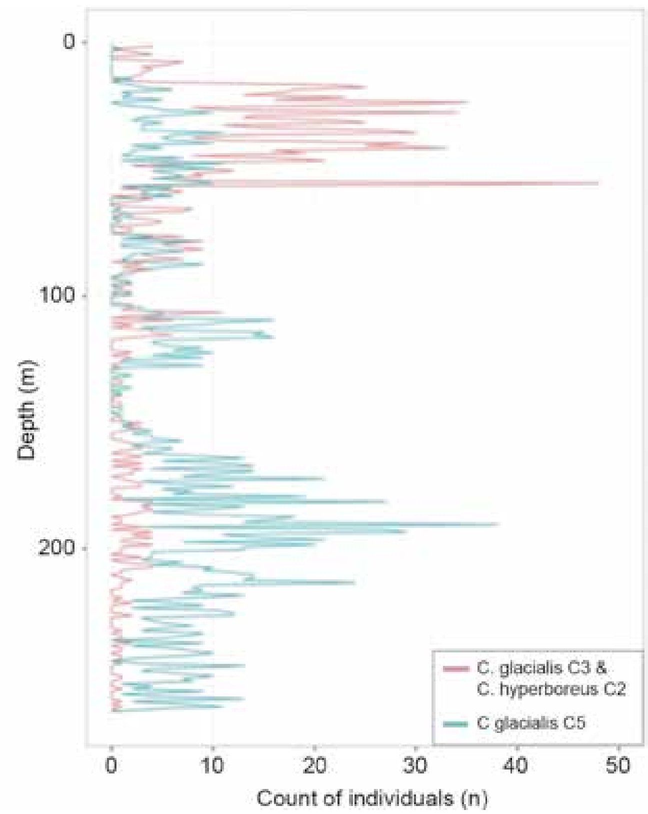

Figure 3. Example of vertical distribution profiles: C. glacialis C5 and the combined group C. glacialis C3 & C. hyperboreus C2 binned at 1 m intervals.

Sea-ice breakup and the recruitment of Arctic cod: interannual comparisons

Hydroacoustic surveys from 2010 to 2014 documented inter-annual variations in the mean standard length, abundance, and biomass of epipelagic fish (95% Arctic cod juveniles). Using satellite-derived ice and sea surface temperatures (SST), we test the hypothesis that an earlier ice breakup and warmer SST in spring-summer promote growth and recruitment of epipelagic age-0 Arctic cod. Large differences in mean standard length of age-0 Arctic cod at the end of August (2 to 5 cm range) were positively correlated with mean SST in spring, during the initial growth season. Mean abundance and biomass within the epipelagic layer of age-0 Arctic cod were significantly higher in years of early ice breakup, which also corresponded to warmer vernal SSTs (Figure 5). Based on length, 99% of Arctic cod captured in the mesopelagic layer (>100 m) were estimated to be from age 0 to 2. Mean abundance and biomass were negatively correlated with the average timing of the ice breakup over the preceding three springs and positively correlated with mean SST in spring over the same three years. This suggests that that the positive impact of an early breakup and warmer SST on larval survival could persist until sexual maturity. Based on several years of observation, these results establish a direct link between Arctic cod recruitment and sea-ice regime and are central to our understanding of the response of this pivotal species to climate change.

Interannual variations in mesozooplankton swimmers in sediment traps: preliminary results

The time series of mesozooplankton abundance in the sediment traps deployed quasi annually at the edge of the Mackenzie Shelf in the Beaufort Sea are weakened by diverse mishaps: the use of different trap models, the lost of moorings, trap malfunction, non deployment in 2013 (helicopter crash), and poor preservation of the samples in some years. Nevertheless, good quality data are now in for the years 2009-2010, 2011-2012, 2012-2013, and 2014-2015, and soon for 2010-2011, and hopefully 2015-2016. These years cover a period of strong interannual differences in sea-ice regime and SST, with particularly late breakup and low temperatures in 2013 and 2014. Preliminary data indicate strong interannual variations in the abundance and, most importantly, the timing of copepod nauplii and other prey of larval and juvenile fish. Interestingly, the series demonstrate the emergence of copepod nauplii under the ice as early as January and February in some years. Counter-intuitively, the abundance of copepod nauplii appears lower in years of early ice breakup when primary production should be higher. In collaboration with LTOO, the determination of the relative availability of ice algae and phytoplankton could help solve this conundrum (Figure 6).

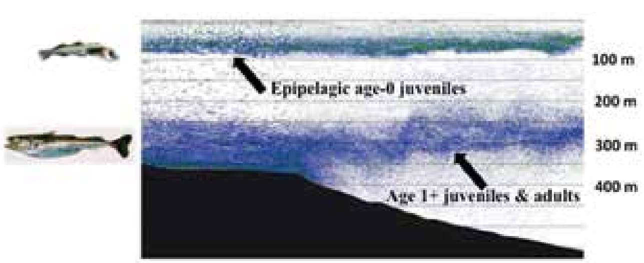

Figure 4. EK60 echogram illustrating the epipelagic layer (0-100m) of young-of-the-year (age-0) Arctic cod and the mesopelagic layer (200-400 m) of age-1+ and adult Arctic cod over the shelf slope in the Beaufort Sea.

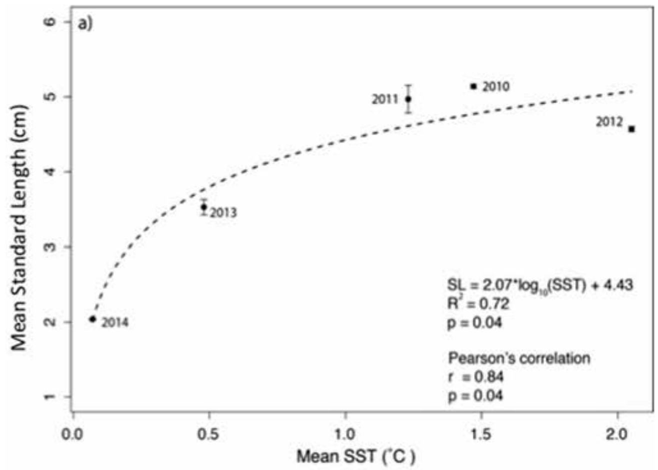

Figure 5. Relationship between the mean standard length of juvenile Arctic cod (as determined from individual Target Strength) in the epipelagic layer of southeastern Beaufort Sea in autumn and sea surface temperatures (SST) in spring-summer from satellites.

ArcticNet Integrated Regional Impact Study (IRIS) for the Western High Arctic

Our team led the preparation of Chapter 4 on marine ecosystems and contaminants. With climate warming and a shift in sea-ice regime, Arctic marine ecosystems are likely to become similar to richer subarctic/ boreal ecosystems over the present century. Presently, the pelagic and benthic ecosystems of the western Canadian Arctic are still essentially intact. However, studies in the Bering Sea indicate that a spectacular shift in the relative importance of the pelagic and benthic ecosystems can occur in less than 20 years. Recent scientific studies in the area point to the following potential transformations: (1) increased penetration of light in the surface layer of the ocean, and increased upwelling of nutrients by wind from the deep layer to the surface layer; (2) reduced production of ice algae and increased production of phytoplankton; (3) enrichment of the pelagic ecosystem to the detriment of the benthic ecosystem; (4) initial improvement of conditions for key arctic specialists such as the large copepod *Calanus glacialis*, Arctic cod and several seabirds until mid-century; (5) a decline in the abundance and health of resident ice-dependant seals and polar bears after mid century; and (6) significant changes in the migration patterns of migratory species such as beluga, bowhead and killer whales. The lack of regional models and scenarios of the future ocean climate in the Canadian western and central Arctic weakens our capacity to forecast precise milestones in the ineluctable transition of the Arctic marine ecosystems towards boreal marine ecosystems. Oil exploration leases overlap with the distribution of Arctic cod and marine mammals. There is an acute need to inventory and increase knowledge about the marine ecosystems of the Kitikmeot region.

The marine ecosystems of the Kitikmeot

As part of the Victoria-Strait-Queen-Maud-Gulf research partnership with Parks Canada funded by the W. Garfield Weston Foundation, we synthesized prior information on the ecosystems of the Kitikmeot as well as the first results of the 2015 pilot project. The marine waters of the Kitikmeot appear as an important transition zone between the western and the eastern North American Arctic. The region comprises important wildlife habitats notably for birds, fish, benthic fauna and marine mammals. The Kitikmeot ecosystem seems characterised by strong spatial variability superimposed on interannual variations and perhaps underlying trends linked to climate warming. Described as a low productivity region on the account of data dating back 10 years, a different picture emerges from more recent data, at least in term of primary production. The present synthesis shows the

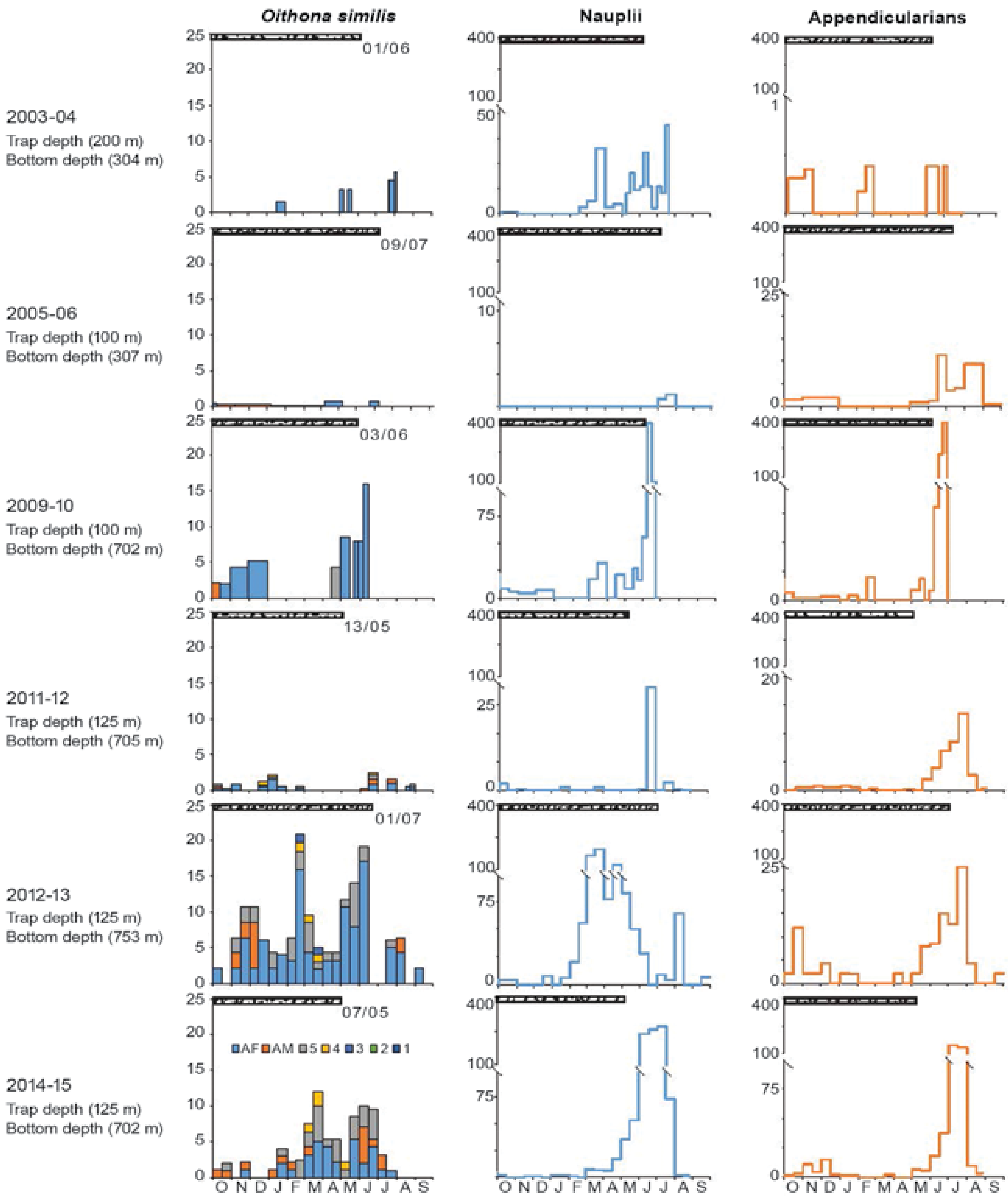

Figure 6. Annual cycles of the abundance of different prey of fish larvae and juveniles (copepod nauplii, appendicularians, Oithona similis) in sediment traps moored at 100 m depth over the shelf slope in the Canadian Beaufort Sea.

uniqueness of the region, and stresses the requirement for a larger effort to be deployed to study regional oceanography and ecosystems. Beside this overarching goal and in light of the preliminary results reported, we formulated several specific recommendations:

- Only half the epibenthic species estimated to occur in the area were sampled so far: continue and spatially enlarge the epibenthic sampling;
- Coronation Gulf appears as an important area for Arctic cod but was never sampled during the *Amundsen* program: include stations in this area in the future;
- Two genetically distinct Arctic cod populations are known to exist in the Canadian Arctic, one in the West and one in the East: analyse the fish collected in the Kitikmeot to determine to which populations they belong;
- We recently formulated the hypothesis that an early ice breakup accelerated the growth of Arctic cod larvae and allowed earlier hatchers to survive: investigate annual variations in larval growth and the hatchdate frequency distribution of survivors using otolithometry in relation to ice breakup timing in the different areas of the Kitikmeot (Figure 7).

DISCUSSION

Since the implementation of the CASES and ArcticNet research programs, we have learned tremendously about the ecology of Arctic cod, its zooplankton prey and its predators, in the Beaufort Sea and elsewhere in the Canadian and Siberian Arctic Ocean. The species distributes in the nearshore zone, the ice cover, and the deep offshore waters. Although ubiquitous, the emerging picture is that most of the biomass of age-1+ Arctic cod is distributed in deep embayments and the slope of the continental shelf, between 200 and 500 m, while the age-0 larvae and juveniles of the year are widely distributed geographically in the epipelagic

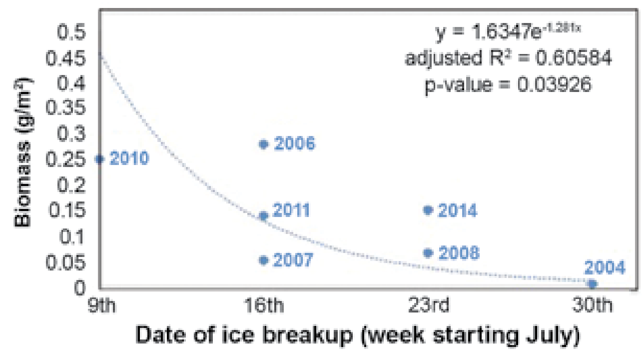

Figure 7. Mean integrated fish biomass in the epipelagic layer (0-100 m) in relation to ice breakup date in the Kitikmeot region.

(0-100 m) layer during the spring and summer months (Benoit et al. 2008; 2014; Geoffroy et al. 2011; 2015). The hatch season is intriguingly long, starting as early as January in the darkness and cold under the full ice and snow cover, and invariably ending in the first week of July (Bouchard and Fortier, 2011). The bulk of hatching in April and May seems to saddle the ice algal bloom and the associated starting production of copepod nauplii (Bouchard et al. 2014). But a large fraction of the larvae hatch well before the onset of intense biological production after the ice breakup.

We proposed that the survival value of hatching so early, under sub-optimal conditions of sub-zero temperatures and paucity of prey, lies in the large size achieved in the fall by surviving early hatchers (Bouchard and Fortier 2011). This large pre-winter size would provide a survival advantage over the first winter. But the question remains: what prey fuel the growth and survival of the early hatchers of Arctic cod (and ice cod, a less abundant sibling species) in winter under the ice cover? Preliminary data from our analysis of the zooplankton swimmers in sediment traps suggest that copepod nauplii, the main prey of the first-feeding larvae, emerge as early as January and February, a result that would explain the otherwise puzzling hatching of Arctic cod and ice cod larvae starting as early as January in the region (Bouchard and Fortier, 2011; Bouchard et al. 2014). The small cyclopoid copepod *Oithona similis*, a prey of the late larval and early juvenile cods, is also present under the ice in winter-spring and early summer. Finally, the appendicularians, on which the early juvenile stages prey heavily, appear later in the season. Most importantly, the multi-year time series indicate large (and sometime unexpected) variations in the timing and intensity of the emergence of these preys. For example, why would copepod nauplii emerge en masse and earlier in 2013, a year of late ice breakup, than in 2012 and 2015, years of early breakup? The on-going analysis of the ice algae and phytoplankton collected by the traps may help solve these conundrums and refine our understanding of how the ice regime influence the prey field of the early stages of Arctic cod.

Meanwhile, the interannual comparison of the acoustically derived abundance and size of Arctic cod juveniles in the fall in relation to the timing of the ice breakup and summer sea surface temperature (SST) is yielding exciting and promising relationships that directly link the reproduction success of this key species to climate variability. The remarkably wide interannual variations in the mean standard length of juveniles in August (2 to 5 cm range) are too large to be explained by temperature-induced differences in growth. We are presently testing that difference in hatching dates rather than growth explain the observed differences in size in early fall. The hatching season of Arctic cod in the Beaufort Sea extends from January to the first week of July. Our hypothesis is that an earlier breakup allows earlier-hatched Arctic cod to survive, resulting in older, larger fish in the fall. According to this interpretation, an early ice breakup would widen the survival window of Arctic cod, enabling early hatchers to survive in greater number and resulting in larger and heavier fish in early fall. What factors are at play that link the early survival of Arctic cod to ice regime? The exact mechanism or combinations of mechanisms by which the early retreat of the ice cover enhances the early survival of Arctic cod remain to be deciphered: increased availability of the preferred prey? Increased availability of light to detect and capture prey? Accelerated growth due to warmer SST? We hope that correlating the early growth recorded in the otolith of juvenile survivors to the prey field recorded by sediment traps, and the summer SST and ice concentration (an index of underwater light availability) fields from satellites over the several years of observation available will provide responses to these pivotal questions.

After one year of activity, the analysis of the time series of sediment trap samples and acoustic records resulted in one disappointment and several encouraging findings. The disappointment is rooted in several gaps in the time series since 2002 (CASES program). For the sediment trap series, gaps were caused in the initial years by factors such as the loss of moorings, the malfunction of traps, poor preservation of the samples, the use of incompatible traps, differences in the depth of the water column for the traps that were recovered, and non-deployment of traps due to the curtailing of the annual mission (e.g. helicopter crash in 2013). Some of these factors are outside our control but several were linked to human error/incompetence/lack of expertise. Rectifiable initial weaknesses in our procedures have been corrected by replacing most of the original mooring team by more experienced personnel and by revising mooring protocols, including the use of the same trap model and the targeting of similar bottom depths. Hence, since 2009-2010 the quality of the data is much better and more stable across years despite gaps due to circumstances out of our control. Weaknesses in the acoustic record during the first years were linked to the lack of pre-calibration of the signal in 2009, loss of records, interannual variations in the track of the ship (within the Beaufort Sea in particular), interannual differences in the timing of the surveys, the curtailing of the annual mission, and insufficient sampling of juvenile and adult fish for the validation of the acoustic signals. Most of these factors have been corrected in recent years and interannual comparisons of Arctic cod abundance, size and biomass is now possible for several regions of the Canadian Arctic Ocean (Beaufort Sea, Archipelago, and Baffin Bay).

CONCLUSION

As reported here, despite gaps in the early years, the analysis of the available multi-year records of sediment trap and acoustic data are yielding several precious new insights into interannual and climate-linked variations in the ecosystem of the Arctic cod. As years of observation accumulate and the quality and consistency of the data improve, such time series become increasingly precious by (1) supplying baseline values and fluctuations of key variables before the full onset of climate trends or industrial impacts; (2) in the case of sediment traps, providing unique information on the complete annual cycle of the ecosystem and its interannual variations; (3) allowing to test precise hypotheses on the mechanisms linking climate and key functions of the ecosystem (e.g. the recruitment of Arctic cod); and, most importantly, (4) ensuring that key observations are maintained as the full impacts of climate change unfold in the Arctic. Hence, the importance of maintaining these time-series until and beyond the end of ArcticNet in 2018 cannot be overstated.

Some countries have been accumulating time series of oceanographic observations in the Arctic Ocean for many years and decades. For example, the annual survey of a northward transect of stations in the Barents Sea north of Norway for several decades, or the Hausgarten observatory maintained by the Alfred-Wegener Institute in Fram Strait. In addition, plans are in the making for the international deployment of a sophisticated observing system in Baffin Bay. Based on our experience, successes and failures in the accumulation of decadal time series of observations in the Beaufort Sea and elsewhere in the Canadian Arctic Ocean, it would be crucial that the protocols used in these different observatories converge in the short term to ensure the comparability and interoperability of the data collected.

ACKNOWLEDGEMENTS

In addition to Canada's Network of Centres of Excellence (NCE) program, *The Arctic cod (Boreogadus saida) ecosystem of the Beaufort Sea: synthesis of decadal records* project of ArcticNet is or has been supported over the years by several collateral funding sources. We thank the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Research Chair program (CRC), the Canada Excellence Research Chair program (CERC), the Canada Foundation for Innovation (CFI), the Canadian International Polar Year, the Beaufort Region Environmental Assessment (BREA) program of Aboriginal Affairs and Northern Development Canada, le Fonds québécois pour la recherche sur la nature et la technologie (FQRNT, volet Regroupements Stratégiques et volet Équipes), and le Comité national pour la recherche scientifique français (CNRS). Major industrial partners such as BP, Imperial Oil Limited and Kongsberg Maritime contributed to our program. We acknowledge fruitful collaborations with several researchers in the Departments of Fisheries and Oceans Canada, Environment Canada, and Natural Resources Canada. None of our achievements could be possible without the expertise and complicity of the personnel, officers and crew of the Canadian Coast Guard. We thank our numerous colleagues in and outside ArcticNet for their expertise and data, with emphasis on our friends at the Center for Earth Observation Studies (U. Manitoba), the Norwegian Polar Institute (U. Tromsœ) and the National Institute of Polar Research in Tokyo. The research results presented here are contributions to the programs of ArcticNet, Québec-Océan at Université Laval, the Takuvik Unité Mixte Internationale, and the Canada Research Chair on the response of marine arctic ecosystems to climate warming.

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The Potential for Natural Oil Spill Biodegradation by Microorganisms in Canada's Arctic Marine Environment

Project Leader

Casey Hubert (University of Calgary)

Collaborator

Joel Kostka (Georgia Institute of Technology)

HQP

Margaret Cramm, Masters Student (University of Calgary)
Michelle Kamula, Masters Student (University of Manitoba)
Oscar Montoya, Masters Student (University of Calgary)
Amy Noël, Masters Student (University of Calgary)

ABSTRACT

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

KEY MESSAGES

- With climate change and declining sea ice cover in the Arctic come increasing opportunities for industrial development and a higher frequency of shipping traffic, e.g., through the Northwest Passage. This elevates the risk of an oil spill or a spill of transportation fuel in Canada's Arctic marine environment.
- A silver lining of the 2010 Deepwater Horizon oil spill in the Gulf of Mexico was the rapid mobilization of naturally present microbial communities that acted as 'first responders' in catalyzing bioremediation and mitigating negative impacts on marine ecosystems. The deep water in this environment is permanently cold, suggesting a similar microbial response in the Arctic may be anticipated.
- Preliminary results from this project have revealed that bacteria in Canada's Arctic ocean are also capable of catalyzing biodegradation of hydrocarbons under cold marine conditions. Genomics has revealed that the Arctic bacteria are relatives of the Gulf of Mexico bacteria, but bear genetic signatures suggestive of being unique to the Arctic marine environment.
- To test this further, ongoing experiments using marine samples from across the Canadian Arctic are being testing for microbial responses to different kinds of contamination scenarios (e.g. diesel, bunker fuel, crude oil) under cold marine conditions. Samples are obtained aboard the research icebreaker CCGS *Amundsen*, and the project involves collaborations with other scientists in Canada, the United States and the EU.

OBJECTIVES

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

- Hypothesis 1: rates of crude oil biodegradation are not limited by low temperature in Arctic marine environments.
- Hypothesis 2: the chemical nature of hydrocarbon mixtures limits biodegradation rates in Arctic marine samples.
- Hypothesis 3: biodegradation of spilled hydrocarbons will be most rapid in areas near hydrocarbon seeps.
- Hypothesis 4: contaminant baselines in sediment cores are influenced by biodegradation below the sea floor.

By testing these hypotheses the project aims to deliver broad outcomes in four areas:

Baselines: Regional maps and tables showing spatial distributions and concentrations of predominant and toxicologically significant hydrocarbon compounds in the Arctic. Any available industry data from the offshore Canadian Arctic can also be included in these maps. Sediment records will incorporate a microbial component to quantify biodegradation over time and assess the extent of the dynamic microbial nature of understanding contaminant baselines.

Microbial Census: First ever characterization of the hydrocarbon-degrading capacity of marine microbial communities across the Canadian Arctic, including identification of key genes and organisms that hold promise as first responders in the event of an oil spill in the permanently cold Arctic marine environment.

Microbial Potential: New understanding of the limiting factors affecting biodegradation of hydrocarbons in the Arctic marine environment with specific focus on oil types and chemistries, as well as the effect of cold in situ temperatures. Importantly, securing results in support of our hypotheses will shift the focus (and fear) away from cold temperature and onto crude oil chemistry as a key variable and driver of biodegradation and will re-shape research dedicated to spill preparedness in general, not just in colder waters. Testing the hypotheses above may also result in their falsification, but this will still deliver crucial knowledge for understanding oil degradation in cold Arctic systems.

Knowledge Transfer to Cold Climates: Support for Hypotheses 1 and 2, that *in situ* temperature conditions are not limiting to Arctic bioremediation, will provide a gateway for the application of microbial biodegradation knowledge obtained in other marine ecosystems to be transferred more directly to the Canadian Arctic; thus policy makers will have at their disposal not only results from this project, but a renewed ability to glean important information from the wealth of results generated from studies focusing on other parts of the world. The collaboration our project has developed with scientists working on the Gulf of Mexico Deepwater Horizon oil spill (Florida based C-IMAGE projects) are strategic and valuable for taking first steps in this direction.

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

1. Geomicrobiology Methods

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

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

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

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

So far, ROV sampling at seabed hydrocarbon seeps has not been possible. Requests have been made in previous years (through collaborators) and as part of this project in 2015, however without dedicated funding for ship time it has not been possible for this project's requests to be granted. Our team in Calgary has had fruitful discussions with the CSSF about ways to modify the ROV sampling infrastructure, and continue to request ROV push coring in our sampling requests for work onboard the Amundsen. We have discussed possible joint applications for ship time (e.g. NSERC STAC) with ArcticNet NIs at Memorial University.

2. Geochemistry Methods

Preparation (subsampling, freeze-drying, determining porosity) and analyses of radioisotopes in sediment cores collected across the Canadian Arctic in 2015 has begun. Radioisotope analyses of duplicate cores from Scott Inlet (a known seep site) have been completed and interpretation and development of a sediment age model is underway.

Radioisotope analyses of samples (sections) from six sediment cores collected by Drs. Hubert and Kuzyk with CHARS personnel during a 2013 expedition aboard the RV *Martin Bergmann* (its first science sampling campaign) near Cambridge Bay, Nunavut (Figure 1) were completed.

The activities of the radioisotopes ^{210}Pb and ^{137}Cs were counted in sediment core sections at the Environmental Radiochemistry Laboratory (ERL) at University of Manitoba. ^{210}Pb (half-life 22.3 years) is a naturally occurring radioisotope produced within the decay series of ^{238}U, which is contained naturally in rocks and minerals and, through in situ decay, gives rise to 'supported' ^{210}Pb activities in soils and sediments (Figure 2). Unsupported or excess ^{210}Pb (^{210}Pbex) in soils or sediments originates from the decay of ^{222}Rn (half-life 3.8 days) in the atmosphere and from the in situ decay of dissolved 226Ra within the water column (Cochran et al., 1990; Kuzyk et al., 2015). ^{210}Pbex is readily deposited by dry or wet fallout to the earth's surface where it becomes linked to sedimentary processes because within the water column, ^{210}Pbex is rapidly scavenged by sediment particles (Appleby and Oldfield, 1978). Radioisotope ^{137}Cs (half-life 30.7 years), a product of nuclear fission, is widely used and recommended as a transient tracer for validating ^{210}Pb-derived sedimentation rates (cf., Smith et al., 2001). It was first released into the environment from nuclear weapons testing in 1952 and its atmospheric deposition peaked ca. 1963, then declined (Wright et al., 1999).

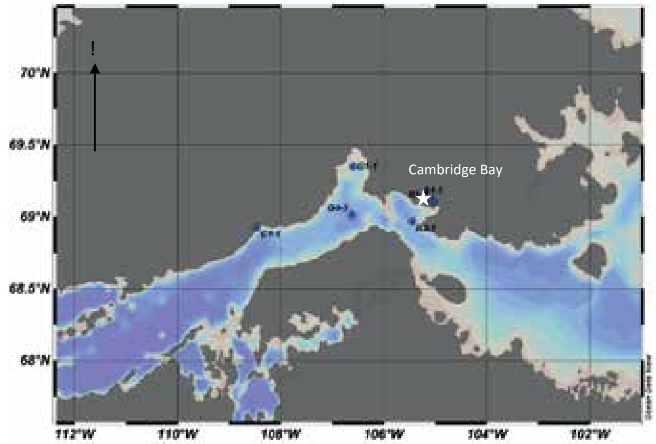

Figure 1. Sediment core locations near Cambridge Bay, NU, sampled by Kuzyk and Hubert in 2013. Geomicrobiological tests on the same samples are still pending.

Sedimentation rates in the cores from Cambridge Bay were estimated by least-squares fitting the natural log of ^{210}Pbex profiles to outputs of a one dimensional two-layer advection diffusion model that accounts for both biomixing and compaction with depth (Kuzyk, 2015). Because most marine sediments are mixed by benthic organisms to a depth of 2-20 cm, which profoundly alters the depth distributions of tracers, biomixing must be taken into account explicitly to accurately determine sedimentation rates. Sediment inventories

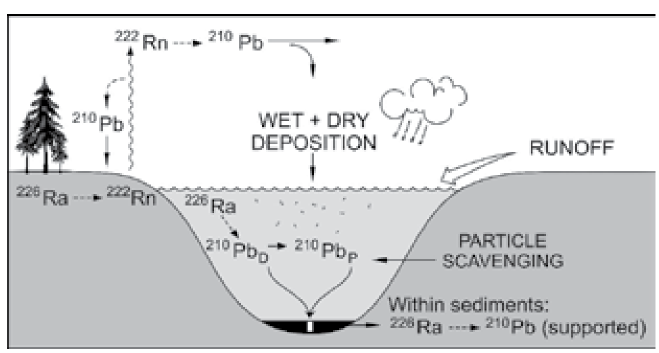

Figure 2. Pathways of radioactive lead (^{210}Pb) and radium isotopes in a marine setting modified from Kuzyk et al, 2015).

of the radioisotopes were quantified and compared across cores to provide insight into sediment sources and sedimentation processes. Inorganic and organic carbon analyses and analyses of stable carbon isotope composition ($\delta^{13}C$), which is a tracer for carbon source (terrestrial vs. marine) was conducted on the core collected immediately adjacent to the community of Cambridge Bay (S1-1). This site was of particular interest because of possible impacts associated with local wastewater disposal and other human activities.

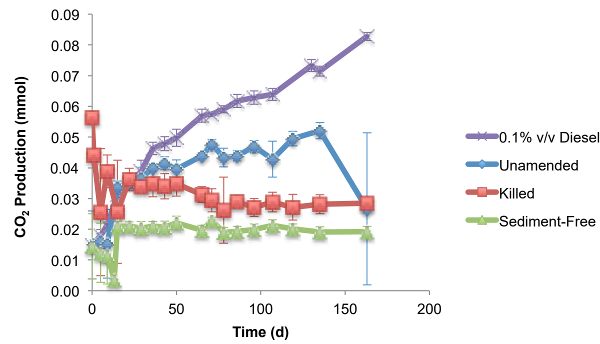

Figure 3. Enhanced microbial respiration in Arctic marine sediment amended with diesel at 4°C. This response is indicative of diesel biodegradation by coldadapted sediment microbial communities.

RESULTS & DISCUSSION

1. Geomicrobiology

Sediment from a known hydrocarbon seep region in Scott Inlet (station PCBC2) was incubated with diesel under oxic conditions. Higher levels of carbon dioxide production were observed compared to diesel-free controls, indicating enhanced microbial activity in the presence of diesel suggesting capability of diesel biodegradation by cold-adapted Arctic marine bacteria (Figure 3). The Illumina MiSeq platform was used generate 16S rRNA gene amplicon libraries from DNA extracted from bulk sediment at the end of the incubation period. Libraries revealed enrichment of bacteria belonging to evolutionary lineages known to include hydrocarbon degraders, like the Alphaproteobacterial *Sphingorhabdus* spp. and the Gammaproteobacterial *Pseudomonas*, *Colwellia*, and *Cycloclasticus* spp (Figures 4-6). Some of these lineages have been detected in oil spill contexts elsewhere other parts of the world, including in the Gulf of Mexico following the Deepwater Horizon accident in 2010. Further analyses will be needed at higher genetic resolution to assess the genotypic similarity between Arctic and Gulf of Mexico relatives. Sediments from the Gulf of Mexico, provided by US project partners, will allow further testing of different metabolic capabilities in these different locations.

Incubation of sediment from Station 314 with diesel under anoxic conditions where sulphate reduction is the predominant redox process resulted in complete consumption of sulphate within eight weeks of incubation at 4°C. All other sites incubated under similar conditions (five Beaufort Sea stations as well as station PCBC2 from Scott Inlet, Baffin Bay) did not display any sulfate reduction over this timeframe (Figure 7A).

Microcosms with Cambridge Bay sediment turned black (indicative of sulphate reduction, i.e., produced sulphide forming FeS precipitate with iron in sediments; Figure 8), further evidencing the activity of cold-adapted sulphate reducing bacteria (SRB) enriched in the diesel amendment.

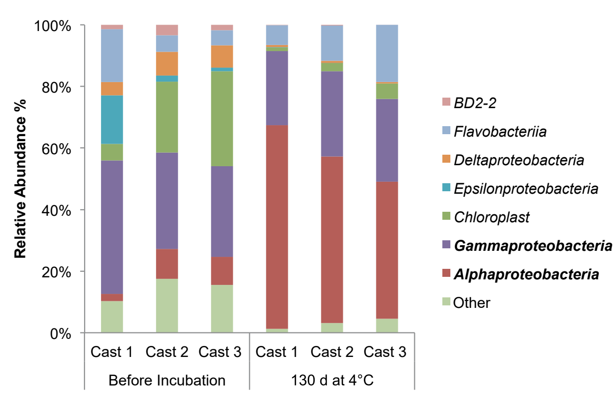

Figure 4. Illumina MiSeq 16S rRNA gene amplicon libraries were prepared for triplicate microcosms. Triplicates were prepared using sediment that was obtained from separate, triplicate box core casts at station PCBC2 in Scott Inlet.

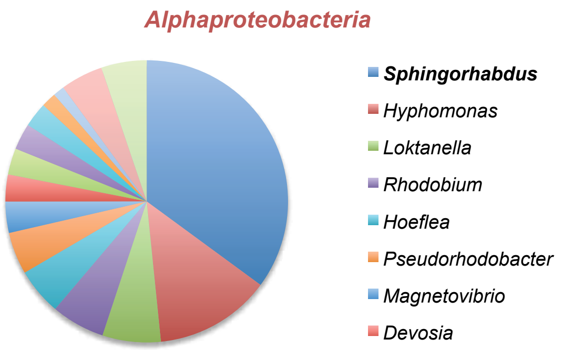

Figure 5. Sphingorhabdus spp. were the dominant Alphaproteobacteria enriched in Arctic (Scott Inlet) sediment from station PCBC2 in the presence of diesel incubated at 4°C. Proportions shown are the mean relative abundance values from triplicate amplicon libraries. Note: The libraries indicate enrichment of cold-adapted Alphaproteobacteria (see Figure 5 for higher taxonomic resolution) as well as prevalence of Gammaproteobacteria (see Figure 6 for higher taxonomic resolution) after 130 days under cold conditions in the presence of diesel (purple line in Figure 3).

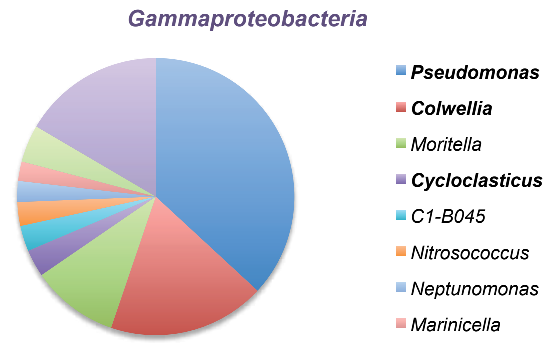

Figure 6. Pseudomonas, Colwellia, and Cycloclasticus spp. were the dominant Gammaproteobacteria enriched in the presence of diesel in Arctic (Scott Inlet) PCBC2 sediment incubated at 4°C. These lineages include well known hydrocarbon degraders from other low temperature marine habitats, including the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

Further investigation using DNA sequence analysis showed significant enrichment of two Deltaproteobacterial genera, *Desulfofrigus* (enriched to 40% of the total microcosm community) and *Desulfotalea* (25% of the total). See Figure 9. These two genera have previously been described as psychrophilic SRB, and their ability to use hydrocarbons as a carbon source has not been reported. There is clearly a difference in microbial community composition at Station 314 near Cambridge Bay, compared to stations assayed in the Beaufort Sea and Baffin Bay, which will be interesting to explore with additional sampling and analysis. This result links well with the complementary sediment geochemistry where we have placed emphasis on the Cambridge Bay region (see geochemistry results below).

2. Geochemistry

The profiles of total ^{210}Pb within the six sediment cores decrease exponentially with depth, consistent with expectations for steady-state sediment accumulation (profile governed by radioactive decay). ^{137}Cs activity in the cores is high near the surface and decreases abruptly in deep sediment sections, consistent with non-steady state ^{137}Cs inputs (deposition associated with atmospheric nuclear weapons testing in the 1950s and 60s). Preliminary sedimentation rates determined for the cores (still to be verified with ^{137}Cs) are 0.06-0.16 cm yr^{-1}. The ^{210}Pbex inventories in the sediment cores increase as water depth increases, consistent with a resuspension and focusing sedimentary regime.

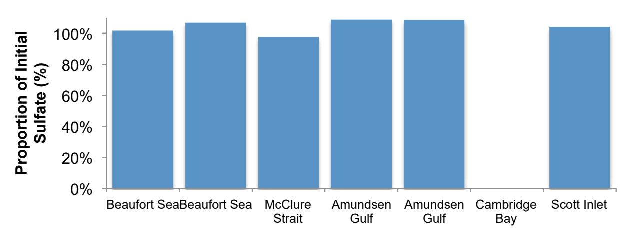

Figure 7. Eight-week incubations of seven different marine sediments under anoxic conditions in the presence of diesel only gave rise to sulphate consumption in Cambridge Bay sediments, suggesting anaerobic hydrocarbon biodegradation potential is high in this region. Each bar reports the mean value from triplicate incubations.

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

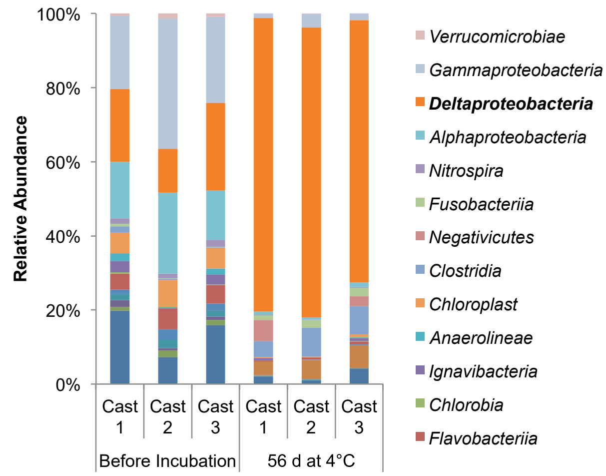

Figure 9. Illumina MiSeq 16S rRNA gene amplicon libraries were prepared for triplicate microcosms. Triplicates were prepared using sediment that was obtained from separate, triplicate box core casts at station 314 near Cambridge Bay. The libraries indicate enrichment of cold-adapted Deltaproteobacteria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

^{137}Cs inventories show a different spatial distribution, reflecting in part inputs from rivers. The organic carbon content of the sediment near Cambridge Bay (core S1-1) was relatively high (~2.4%) compared to typical sediments in the Canadian Arctic Archipelago. The $\delta^{13}C$ values were relatively enriched, reflecting inputs of marine (algal) production as the major organic carbon source.

Well-dated sediment cores represent extremely valuable natural archives from which contaminant and microbial baselines may be properly interpreted. They ensure that contaminant and microbial data are being considered over relevant time scales. They also allow understanding of whether environmental conditions are static or dynamic. The radioisotope data obtained for the sediment cores collected near Cambridge Bay indicate that these cores contain intact archives in which contaminant and microbial data are laid down in chronological order, despite some (low level of) surface biomixing. The preliminary sediment age models that we have determined for the cores suggest geochronologies consistent with those determined in other cores in the Canadian Arctic Archipelago (Kuzyk et al., 2013). Organic C and $\delta^{13}C$ tracer data suggest that marine (algal) carbon sources are very important close to the community of Cambridge Bay and the accumulation of their remains on the seafloor has produced an organic-rich sediment. A rich benthic microbial community may be expected at this site. It seems likely that there has been enhancement of nutrient supply to coastal waters, possibly associated with local human activities such as wastewater discharge.

CONCLUSION

Initial results confirm that hydrocarbon biodegradation under cold Arctic marine conditions is possible, and further work will build on this initial discovery to test hypotheses and deliver outcomes that were proposed. 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. Sediments from Cambridge Bay have been analysed for sediment accumulation dynamics and offer an opportunity for comprehensive baseline determinations that incorporate both microbial diversity and sediment geochemistry, including a chronological component.

ACKNOWLEDGEMENTS

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

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Freshwater-Marine Coupling in Hudson Bay: a Study of Winter Estuarine Processes in the Coastal Corridor in Southeast Hudson Bay and Effects of Environmental Change

Project Leader

Zou Zou Kuzyk (University of Manitoba)

Network Investigators

Jens Ehn (University of Manitoba)
Celine Gueguen (Trent University)

Collaborators

David G. Barber (University of Manitoba)
Igor Dmitrenko (University of Manitoba)
Ryan Galley (University of Manitoba)
Mats Granskog (University of Manitoba)
Joel Heath (Simon Fraser University)
George Liu (University of Manitoba)
David Lobb (University of Manitoba)
Jennifer Lukovich (University of Western Ontario)
Robie W. Macdonald (Fisheries and Oceans Canada - Institute of Ocean Sciences)
Christine Michel (University of Manitoba)
Jean-Eric Tremblay (Université Laval)

HQP

Vlad Petrusevich, Doctoral Student (Centre for Earth Observation Science (CEOS))
Geophysical and Biological Tracers in Water Dynamics of Arctic Shelf and Estuaries
Annie Eastwood, Masters Student (University of Manitoba)
Mairi Fenton, Masters Student (University of Manitoba)
Michelle Kamula, Masters Student (University of Manitoba)
Eva Slavicek, Technical Staff (University of Manitoba)
Hakeem Adediran, Undergraduate Student (University of Manitoba)
Samantha Huyghe, Undergraduate Student (University of Manitoba)

Northern HQP

Lucassie Arragutainaq, Northern Research Staff (Hamlet of Sanikiluaq)
Ita Kanayuk, Northern Research Staff (Hamlet of Pangnirtung)
Pauloosie Kasudluak, Northern Research Staff (Community of Inukjuak)
George Lameboy, Northern Research Staff (Community of Chisasibi)
Jack Niviaxie, Northern Research Staff (Kativik Regional Government)

ABSTRACT

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

KEY MESSAGES

- Hudson Bay is experiencing rapid environmental change, driven by climate warming and hydrological alterations associated with hydroelectric development.
- Both of these changes directly operate on the hydrological cycle within the Bay either through the sea-ice formation/melting cycle (climate) or through the runoff cycle (development).
- The dynamic coastal corridor in southeast Hudson Bay is especially sensitive to hydrological change because it is the entry point for rivers thus accounting for most of the runoff transport, the location where much of the sea ice melts, and because it contains many polynyas, which are crucial for biota and the humans that depend upon marine biota for country food.
- Although there are some historical data for the open-water period, virtually no data have been collected for the polynya regions during winter-early spring, the crucial time period for wildlife, and also the time of year that now dominates river inflow.
- In this project, a team of university researchers and Inuit and Cree from five communities are studying the winter conditions and processes in the coastal corridor in southeast Hudson Bay. This study addresses key data gaps in our understanding of the interactions between fresh water, sea ice, stratification and polynya processes to provide the basis to determine the effects of hydroelectric regulation and climate change. Focus on the polynyas addresses concerns raised by local communities and represents an important contribution to the ArcticNet Hudson Bay IRIS.

- The project has already generated a large amount of new data about the freshwater distributions, and interactions between runoff, sea-ice melt and sea-ice formation. With these new field data, we may now test hypotheses on how change in hydrological and/or sea-ice cycles is likely to affect this polar estuary.
- Extensive winter field observations and sampling from the landfast sea ice began in winter 2015, is continuing in January-March 2016, and will continue annually throughout the duration of the project. Late summer (open-water) sampling will be conducted along the coast and from the CCGS *Amundsen* in 2017 to provide the initial conditions at the beginning of winter, also a crucial time for polynya formation.
- The isotopic data obtained in the first year of the project specifically indicated the considerable importance of river water throughout southeast Hudson Bay in winter. The project will investigate how this river water affects sea-ice formation, sea-ice properties (important for travel), winter mixing, surface nutrient replenishment, and deep water formation.

OBJECTIVES

In the first year of our project, we have made progress on the following objectives, as stated in our proposal:

- Document the spatial patterns, temporal evolution and inter-annual variability in freshwater distribution in winter in the coastal corridor in southeast Hudson Bay;
- Quantify the freshwater sources and calculate inventories of the components in the water column;
- Characterize the deep water in Hudson Bay, with an emphasis on gaining insight into key sea ice formation and water modification processes and sites (e.g., polynyas), and interactions with freshwater distribution.
- Use a combination of established and novel tracers to differentiate river waters and shelf waters from different regions and obtain a baseline for evaluating future change in the freshwater budget.
- Evaluate whether past oceanographic model outputs and offshore data collected from the CCGS *Amundsen* and moorings reflect conditions in coastal areas, which are of great importance to Inuit and Cree communities.
- Build collaboration in research activities, develop strong lines of communication, and provide information relevant to the concerns of citizens in the communities along the coastal corridor in southeast Hudson Bay and of relevance to the IRIS.
- Promote knowledge exchange, research networking and linkages and ultimately help increase the capacity of partner organizations and communities to collectively participate in and benefit from community-driven research initiatives.
- Contribute to the goals and objectives of complementary research efforts, including the NSERC Collaborative Research and Development (CRD) project (“BaySys”) that is also collecting data in Hudson Bay, through strong communication and coordination of planning, cost-sharing of equipment, instruments, and information, co-participation of the research team in both projects.

These objectives cannot fully be achieved in one year and some (e.g., characterizing the deep water) depend in large part on sampling from the CCGS *Amundsen*, which will not occur until June 2017. Winter sampling success is contingent on the extent and distribution of landfast ice cover. Also, there are few ‘deep’ sites safely accessible in winter from the landfast ice.

An additional objective stated in our proposal was to apply currents derived from the NEMO model, together with freshwater inventories, to calculate fluxes in the coastal corridor. This objective will be addressed in years two and three of our project when sufficient data and modeling results are available.

INTRODUCTION

Our goal is to improve the understanding of freshwater sources, the distribution of runoff in the ocean, and their interactions with ice formation/melt and other processes in Hudson Bay. In particular, our emphasis is on winter estuarine processes in the southeast coastal corridor. Hudson Bay is experiencing rapid environmental change, likely a product of both global drivers (warming) and local drivers (hydroelectric development and regulation of rivers), which interact to affect the hydrological cycle. In southeast Hudson Bay, there is great community concern centered specifically on cumulative impacts of these changes on adjacent marine habitats. Hunters have noted changes affecting their traditional land-use practices (e.g., winter travel, wildlife harvesting in coastal areas, including polynyas and eel grass beds) (AES, personal communication).

The coastal corridor in southeast Hudson Bay is a prominent 'double estuary' – at times, freshwater is supplied by river input and ice melt such that the surface waters become lighter due to freshening (positive estuary), whereas at other times, ice grows rapidly in polynyas and flaw leads and leaves behind enhanced amounts of brine, such that the waters become denser by cooling and the addition of salt (negative estuary). Historically, the freshwater cycles and sea-ice cycles have been synchronized such that freshet and ice melt occur during the spring-summer melt period, and the withdrawal of freshwater by sea-ice co-occurs with low winter river inflows. This cadence generally produces a seasonal separation between positive and negative estuaries (the former operating in summer and the latter in winter). However, considerable freshwater may, nevertheless, remain in winter in Hudson Bay (cf., Freeman et al., 1982). Hydroelectric developments have strongly altered the runoff cycle by holding back river water for use (power generation) during winter.

The amount of freshwater remaining in southeast Hudson Bay in winter is poorly documented but must have increased in recent decades consequent to hydroelectric regulation. Southeast Hudson Bay is downstream of the large regulated rivers both in Manitoba (Nelson) and Quebec (La Grande Complex). In the La Grande River system, for example, there has been a ten-fold increase in winter discharge compared to ~1976. Over the same time period, the ice climatology has also changed widely in the Bay as manifested by a longer open water season (i.e., a 3-week increase on average since the mid-1990s (Hochheim and Barber, 2014)).

These substantive changes in the freshwater cycles imply that the annual functioning of the estuaries, which collectively form the boundary region of Hudson Bay, must also have changed. If so, this change has strong implications for the physical and biogeochemical processes affected by ice cover and ocean stratification in the Bay, such as the rate, timing and quality of sea-ice formation, the depth of winter mixing and hence replenishment of nutrients to the surface layer, and the rate of deep-water formation and ventilation. Changes like these directly affect the timing, amount, and type (ice, pelagic, benthic) of primary production, the access of higher trophic levels to that production, and the conditions of deep water including oxygen content. While sea-ice provides one control on these processes, the ocean provides another. Specifically, stratification, estuarine circulation, upwelling forced by winds, and tides also affect water properties (Dmitrenko et al., 2012). Sensitivity to both ice and ocean processes means that Arctic double estuaries are uniquely sensitive to environmental change and cannot be understood by reference to estuaries that do not form sea ice (Macdonald, 2000). Impacts of changes in the functioning of landfast ice or polynyas in southeast Hudson Bay will be felt keenly by Northerners and, indeed, northern communities have frequently raised concerns about changes they have observed in Hudson Bay's coastal zone.

With major hydroelectric developments recently completed, and climate-related changes accelerating, there is an immediate need to obtain data informing us about the wintertime functioning of this coastal corridor. The processes potentially affected by these changes, such as landfast ice formation, winter convection, and the formation and ventilation of deep waters, all impinge on the freshwater balance and distribution in coastal waters. This project represents a community-based research effort to obtain these data.

ACTIVITIES

Field Work

Overview: In 2015-2016, the principal focus of the research was obtaining winter field-based data on ice and oceanographic conditions in the coastal corridor of southeast Hudson Bay, and interpreting these data to gain information about the winter functioning of this estuarine system. Prior to receiving ArcticNet funding, we had already been working to establish community-based research collaborations that would make such winter sampling and observations possible.

- In January 2014, preliminary field assessment and sampling was conducted at Sanikiluaq, Nunavut. Eight sites were sampled and profiled, and a mooring with CT sensors and ADCPs was deployed for a one-month period. In October 2014, four sites were revisited to obtain samples reflecting the open-water period. This early work set the stage for our proposal to ArcticNet.
- In January-March 2015, we conducted sampling and observational programs centred at Sanikiluaq, Nunavut. We also expanded the observational program to four additional sites along the James Bay and southeast Hudson Bay coasts. The specific fieldwork activities in each region in 2015, the lab analyses, results and discussion are presented in detail below (with reference to 2014 results as appropriate).
- In January 2016, we launched our winter 2016 observation and sampling program. At the time of preparation of this report, three university team members were deployed to the field to work with community research partners at two different sites. It is expected that these field activities will be continued right up until the end of the fiscal year and into April 2016. These activities are described in the 2016-2017 Planning Section.
- A key component of our project is the exchange of knowledge with community research partners, and obtaining and providing information relevant to the concerns of citizens in the communities along the coastal corridor in southeast Hudson Bay and of relevance to the IRIS. In 2015, an open house/consultation was conducted in each community where field work occurred. There was excellent engagement of community research partners as evidenced by the data collection efforts even when university researchers were not present. Several members of the project team are also actively engaged in the Hudson Bay IRIS process, serving on the steering committee and taking a leadership role in coordinating or drafting portions of chapters. Major advances were also made in 2015 in development of the interactive mapping platform associated with the project (IK-MAP) (see article in The Walrus by Rustad, December 2015). These activities are led by the Arctic Eider Society and are described in the networking section.
- Also of relevance to the IRIS, in May 2015, one of our team members (Dr. J. Heath) was invited by the Canadian Studies Center at the University of Washington to participate together with 14 other scholars from Québec, Canada, Australia, and the United States in an all-day workshop called Québec Policy on the Arctic: Challenges and Perspectives. Dr. Heath worked with Lucassie Arragutainaq to write a short report on this topic based in part on their experiences working on this project. The workshop and report help contribute to our objectives of promoting knowledge exchange, research networking and linkages and

ultimately helping increase the capacity of partner organizations and communities to participate in and benefit from community-driven research initiatives.

Sanikiluaq-based fieldwork: The winter 2015 field season commenced early January and ended mid-March. Two university researchers (HQP1 and 2) joined Dr. Joel Heath (Arctic Eider Society) and community researchers (Lucassie Arragutainaq, Hunters and Trappers Association, coordinator) in Sanikiluaq to conduct this work. The team travelled from the community each day (weather permitting) to sampling sites located along the outer coastline of the Belcher Islands (Figure 1).

- At each designated site, a conductivity-temperature-depth (CTD) sensor was deployed through a hole drilled in the landfast ice to obtain a profile of the water column. The data were downloaded daily upon return to warm quarters in the community. Both Sontek Castaway and RBR CTDs were used and an inter-comparison was completed to ensure good repeatability.
- Water samples were collected at specific depths (generally 1 m, 5 m, 10 m, 20 m, and near-bottom) for subsequent analysis of salinity and various other tracers and properties. Water was captured in a plastic Kemmerer and stored temporarily in 1 L brown Nalgene bottles, until processing and subsampling could be conducted back at a warm facility in town. In transit, bulk water samples were stored in insulated coolers containing several hot-water bottles to prevent freezing. Water samples were subsequently distributed into plastic and glass vials according to the specific analytical requirements.
- In terms of the schedule of sampling and observation, CTD profiles were conducted at regular (biweekly) intervals throughout the entire season. Community researchers conducted additional profiles in the absence of university researchers to ensure good temporal coverage. Water samples were collected during each visit of the university researchers.
- During the last water sampling event of the season, ice cores were retrieved from designated sites. Ice cores were obtained because they

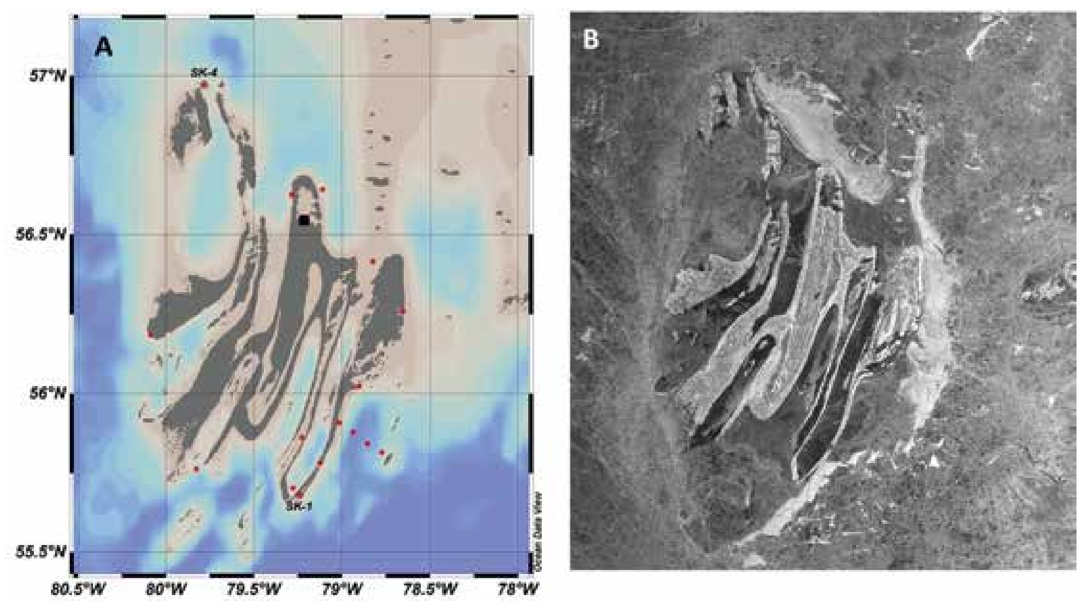

Figure 1. Map showing winter 2015 sampling sites around the Belcher Islands (A) and image of the ice conditions at the time of sampling (B).

may record the change in surface freshwater content throughout the winter season. A Mark II ice corer was used to collect nine centimeter diameter, 100 cm long ice cores. Each ice core was cut immediately on site into 5 cm sections, which were then placed in labelled plastic ziplock bags. The core sections were kept frozen to prevent any changes to the physical composition of the sample. Back in a warm facility, ice core sections were melted (without headspace) and the melted samples then distributed into vials for various lab analyses.

- A mooring program in which instruments were hung from the landfast ice was initiated in the Sanikiluaq area in winter 2015. Deployment occurred in early January and retrieval in early- to mid-March (depending on site accessibility and ice conditions). Six conductivity-temperature (CT) sensors were mounted on a vertical array together with two current meters (Figure 2) at a site at the southeast corner of the Belcher Islands (SK-1). Four additional CT sensors were placed ~1.5 m below the bottom of the ice at spatially distributed sites around the outer coast of the islands. At one of these sites (SK-3), an additional CT was placed at a depth of 5 m below the bottom of the ice.

Coastal Hudson Bay and James Bay fieldwork: Winter fieldwork was also conducted in 2015 around the communities of Inukjuak, Umiujaq, Kuujjuaraapik (in southeast Hudson Bay) and Chisasibi (in James Bay) (Figure 2). This work represented the first (pilot study) year of a multi-community research network in southeast Hudson.

- In each community, we conducted a community meeting/information session, wherein the goals and objectives of the research were discussed (following up prior email and phone communications).
- Proposed sampling sites were reviewed and refined based on traditional knowledge of ice conditions and travel feasibility/safety.
- Community researchers received training on the research method and instruments, including especially the CTD and CT sensors. We also demonstrated the collection and field processing of ice core samples. Several CTD casts were then performed from the landfast ice around each community while the university researchers were present.

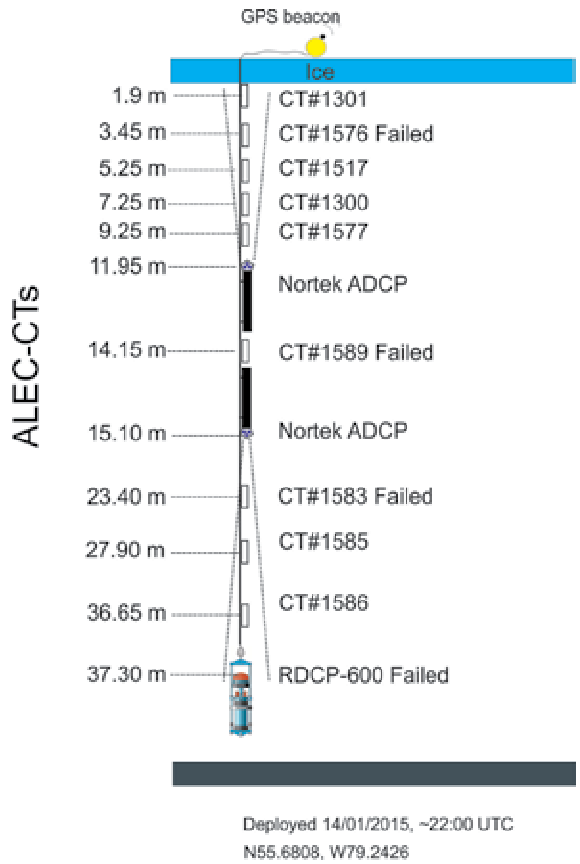

Figure 2. Mooring diagram with instrument depths for the 2015 installation at site SK-1 southeast of the Belcher Islands.

- Around several of the communities, community research partners made additional CTD casts at regular intervals through the duration of the 2015 season. In total, this work yielded a data set of more than 50 CTD casts. These data were displayed in a nearly real-time manner using the interactive mapping platform (IK-MAP) associated with this project (Figure 3).

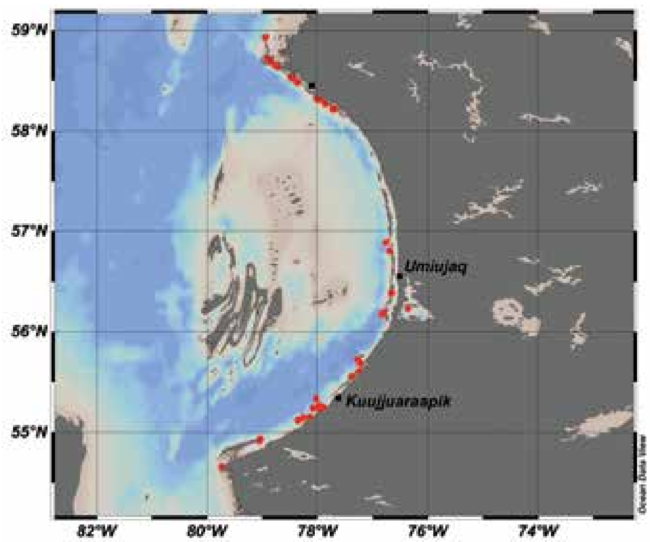

Figure 3. Map showing winter 2015 CTD profiling sites along the southeast Hudson Bay coastline.

- A CT sensor was deployed for a period of more than two months just under the ice at the mouth of James Bay (near Long Island).

Lab Analyses

- Salinity was determined in water and melted ice samples at the Department of Fisheries and Oceans (DFO), University of Manitoba campus, using a Guideline Portasal (model 8410A). The machine was calibrated with 34.8 ppt OSIL standard seawater (salinity specific to batch) before and after each day of analysis.
- Oxygen isotope ratio of water ($\delta^{18}O$) in water and melted ice samples was determined using a Picarro Cavity Ring-Down Spectroscopy (model L2130-i) High Precision Isotopic Water Analyzer at the University of Manitoba. The precision of the instrument is 0.025‰ when measuring $\delta^{18}O$ in a freshwater sample. Each sample was analyzed six times in total, with only the last three measurements being used to obtain an average isotopic ratio. Samples were compared to the international V-SMOW standard.
- In addition to salinity and $\delta^{18}O$, water column samples were submitted to the laboratory of Dr. Jean-Éric Tremblay, Laval University, for nutrient analyses, and to the laboratory of Dr. Celine Guéguen, Trent University, for chromophoric dissolved organic matter (CDOM) and stable tracer (Ba, Sr, U) analyses.
- Data processing and QA/QC checks were conducted on the CTD and CT sensor data sets. To verify that the CTD data were not affected by freezing of the instrument, observed temperatures were compared to the expected freezing point of seawater at the observed pressure and salinity. CTD data were also compared to measured salinity (bottle) data, where available.

Data sharing/Communications

Important objectives of this project include building collaboration in the research activities, developing strong lines of communication, and providing information relevant to the concerns of citizens in the communities along the coastal corridor in southeast Hudson Bay and of relevance to the IRIS. To this end, all of the data collected during the 2015 winter field program were incorporated into the interactive communication platform associated with this project, IK-MAP (Interactive Knowledge Mapping Platform).

- Considerable development work was invested in IK-MAP in 2015 to ensure that the way in which the information generated in this study is presented to community members is understandable (i.e., form and content).
- After using the data generated in winter 2015 to thoroughly test the platform, it was launched for community use (beta level). Initial feedback is that it provides a very useful tool for the project team and for linking this group to the broader community.

RESULTS

Overview

We identified and provided initial training to new community research partners in southeast Hudson Bay. We continued training three graduate students at UM who have been with us since 2014 and recruited two undergraduates and two new graduate students (January 2016 start) who will be long term contributors to the project.

Within the Sanikiluaq (Belcher Islands) area we obtained the first significant wintertime ice/ocean data set, including CTD casts, bottle (water) samples, ice samples, and mooring data, which we have been analyzing to determine:

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

Each of these activities addresses our project objectives. During the winter of 2015, we also obtained CTD profiles from widely distributed sites along the southeast Hudson Bay coast.

The data collected in the Sanikiluaq area in 2015 comprise parts of a Master's thesis project for Rosemary (Annie) Eastwood and a PhD thesis for Vladislav Petrusevich. Both students have completed their field work (data collection) and are in the process of completing their interpretations of the results and preparing manuscripts for publication in the peer-reviewed literature. The data collected along the southeast Hudson Bay coast in winter 2015 will help inform student projects that are getting underway in January 2016.

Freshwater distribution in space and time

In summer, the coastal corridor in southeast Hudson Bay is the key transporter of freshwater from major source areas (rivers) in southern Hudson Bay and James Bay, northward to Hudson Strait. Borne by strong coastal currents, some freshwater from southern Hudson Bay reaches Hudson Strait by late fall/winter. It is not known to what extent freshwater remains in southeast Hudson Bay in winter, where it may interact with ice formation processes.

CTD profiles obtained in January 2015 show a weakly stratified water column with relatively fresh surface waters (salinity ~25) and low salinities extending

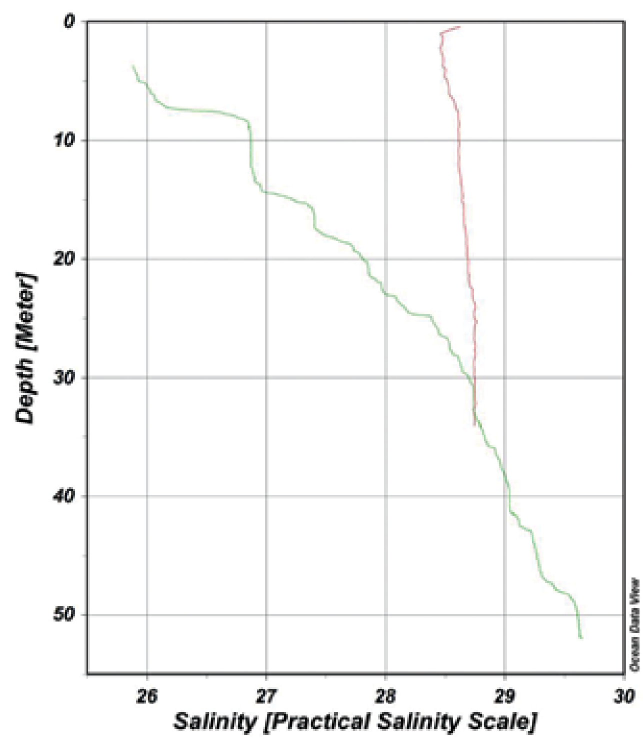

Figure 4. Salinity profiles in January 2015 at site SK-1 in the coastal corridor southeast of the Belcher Islands (green line) and site SK-4 northwest of the Belcher Islands (red line). Locations of these sites are shown in Figure 1.

down to depths of about 30 m at sites in the coastal corridor and east/southeast of the Belcher Islands (Figure 4). By comparison, the sites northwest of the Belcher Islands the water column had a uniform salinity of approximately 28.5 (Figure 4). A salinity and temperature time series obtained from the mooring deployed east/southeast of the Belcher Islands shows that the stratified water column with low surface salinity generally persisted until mid-March (Figure 5), although there was a gradual increase in salinity to about 27. At sites north and west of the Belcher Islands, surface salinity hovered at around 29 and 28, respectively, throughout February-March (not shown).

Along the southeast Hudson Bay coast, surface salinity in January-February 2015 was ~24 near the mouth of James Bay (Cape Jones), ~25 near Kuujjuaraapik (outside the localized plume of the Great Whale River) and ~26 northward along the coast to Umiujaq (Figure 6). A slightly fresh but cold (near the freezing point) layer extended to a depth of about 20 m in the southern portion of the coast and to 25-30 m further north.

Freshwater sources

In addition to river runoff, the seasonal addition of sea-ice melt represents an important source of freshwater to the Hudson Bay system. In southeast Hudson Bay, the seasonal input of river runoff has been estimated at 4-6 m and sea ice melt at 1-2 m (Granskog et al., 2011). On the other hand, it is expected that considerable brine is added to the surface waters in southeast Hudson Bay through the process of ice formation in winter. However, the relative contributions of sea ice melt (or brine) and river runoff to the total freshwater budget in this region in winter have not been directly assessed.

Our data, which include profiles of salinity and $\delta^{18}O$ in water and ice, are being used to determine relative contributions of river water, and seawater in samples taken along the outer coast of the Belcher Islands in January-March 2015. We are finding fairly large fractions of river water near the surface, with evidence also of the brine cycle in the water due to sea ice

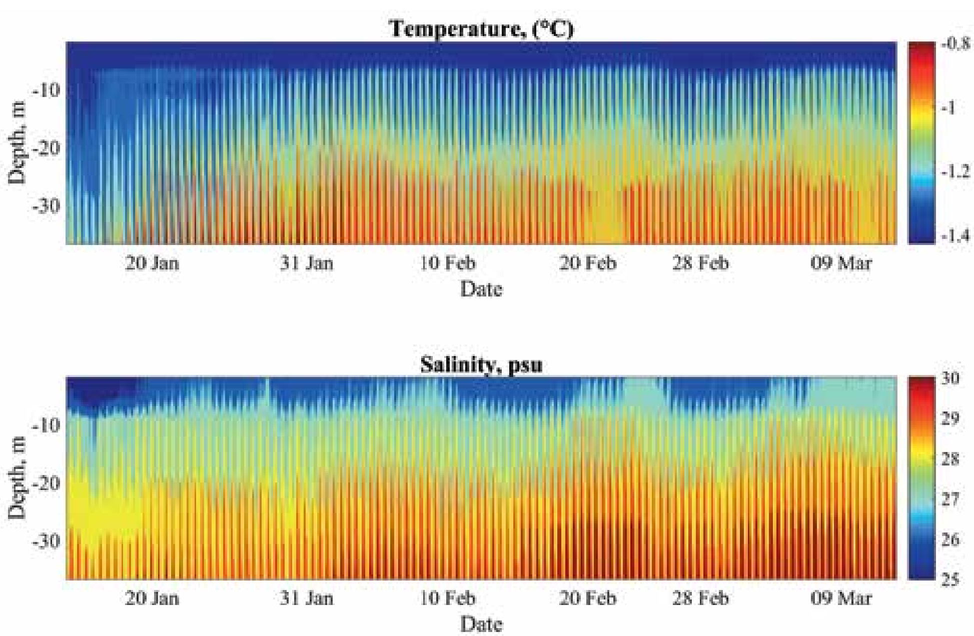

Figure 5. Time series of temperature and salinity spanning January to March 2015 at a site (SK-1) southeast of the Belcher Islands.

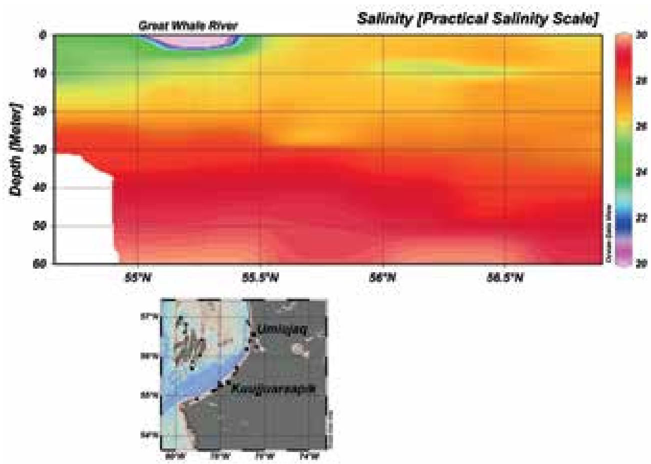

Figure 6. Salinity under the landfast sea ice in January-February 2015 along a south-north section extending from the mouth of James Bay (Cape Jones) to Umiujaq.

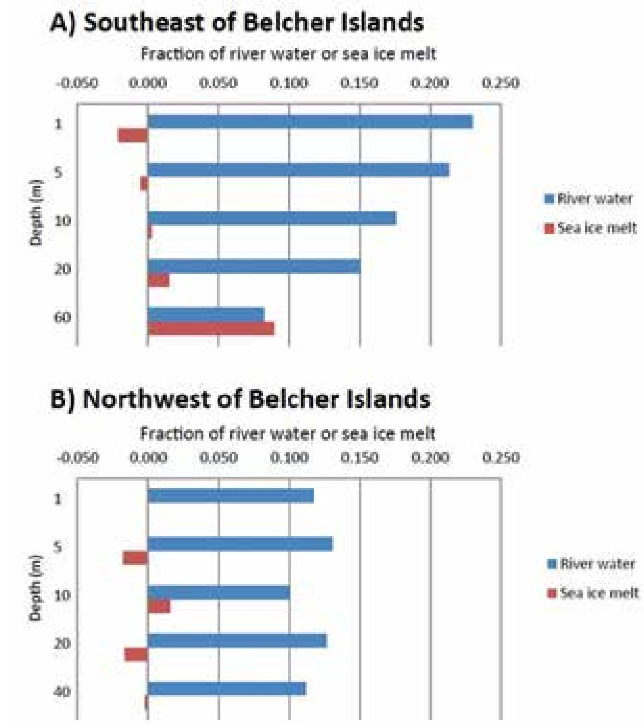

Figure 7. Fractions of river water and sea ice melt at various depths in the water column southeast of the Belcher Islands (A) and northwest of the Belcher Islands (B). Fractions were estimated using salinity and $\delta^{18}O$ data together and end-member values used previously in Hudson Bay.

melt in spring and sea-ice formation over winter. The isotopic characteristics for river water proposed by Granskog et al. (2011) have been found appropriate also for southeast Hudson Bay based on a sample of the discharge from the La Grande Complex.

We estimate that river water comprised ~23% of the surface waters (top 5 m) southeast of the Belcher Islands in January 2015 (Figure 7), which is substantially greater than the ~12% for waters northwest of the Belcher Islands at the same time period. In the preceding October (pre-freeze up), river water comprised ~13% of the upper water column (top 20 m) southeast of the Belcher Islands.

The effect of ice formation/melt cycle is evident in water sampled at 60 m (site SK-1) in January, which still contained net sea ice melt (positive fractional values, Figure 7). Presumably this reflects residual from sea-ice melted at the surface during the previous summer/fall, and that the cumulative sea ice formation in this region up to the point of sampling (mid-January) was insufficient to affect the properties of the deep waters (~60 m) by convection or advection. There was about 50 cm of landfast ice in the area at the time of sampling. Throughout the remainder (upper portion) of the water column, the net fraction of sea ice melt was approximately zero. Neutral sea ice melt fractions were also found throughout the water column (to 40 m) northwest of the Belcher Islands in January.

Interannual variability

We have now obtained salinity and $\delta^{18}O$ data from around the Belcher Islands during two consecutive winters (2014, 2015) that may be compared to data collected in the same area during the fall of 2014 (Figure 8). There is a general covariance of salinity and $\delta^{18}O$ in the data sets from each season, which strongly implicates river water as a primary influence on many of these samples. The winter data (from both years) are also displaced to the right relative to the fall data, which is consistent with the addition of salt to the water column during sea ice production. The greater displacement for winter 2014 data implies that there have been greater additions of salt to the water column. Depending on fall conditions, this likely indicates greater sea ice production.

Potential additional freshwater tracers

At least two "conservative" tracers (e.g., salinity and $\delta^{18}O$) are required to distinguish between river runoff and ice formation/melting in Hudson Bay. To further differentiate between fresh waters from different rivers (e.g., Nelson River/southwest Hudson Bay vs. La Grande Complex/James Bay), additional tracers are required.

For the winter sampling in 2015, we also collected samples for dissolved nutrients, absorbing and fluorescing dissolved organic matter (CDOM and FDOM, respectively), and Sr concentrations and isotopes ($^{87/86}Sr$) to evaluate their potential as added tracers. Results are now available for a detailed study of the behavior of Sr in estuaries (Gueguen et al., 2015) (Figure 9). Both Sr and $^{87/86}Sr$ are conservative in the Nelson and Great Whale River estuaries. Small

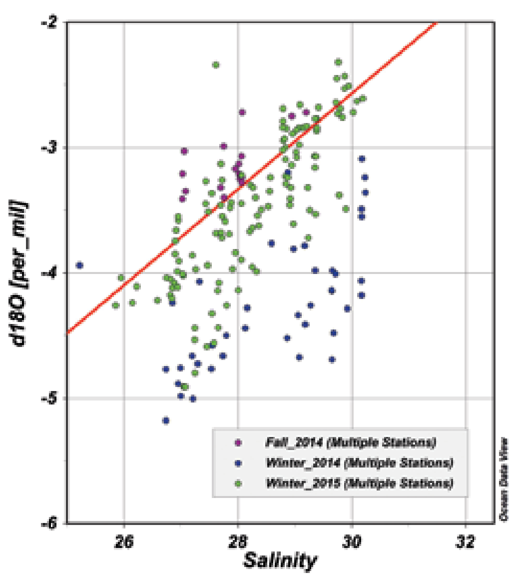

Figure 8. Plot of salinity vs. $\delta^{18}O$ for sites around the Belcher Islands sampled in winter 2014, fall 2014, and winter 2015. The red line reflects two endmember mixing (river water – sea water) without the influence of the sea ice formation/ melt cycle.

deviations in the conservative behavior of $^{87/86}Sr$ may result from desorption/ exchange of Sr from particles (resuspended sediment) in the turbid Nelson River estuary. Other samples collected around the Belcher Islands have been analyzed in the lab but interpretation is still ongoing.

Biogeochemical and biological implications of changing ice/ocean conditions

Although ice is undeniably the most obvious feature distinguishing Arctic seas and directly relevant to Arctic wildlife and people, there are other less-visible factors that are also of great importance in terms of how change will occur in these areas (Macdonald et al., 2015a). Of particular importance are river runoff and its constituents (sediment, nutrients, terrestrial organic matter).

Stemming in part from our work in Hudson Bay, where river inflow plays such a dominating role, we prepared two review papers in 2015 (entitled: "It is not just about the ice: a geochemical perspective on the changing Arctic Ocean" and "The vulnerability of Arctic shelf sediments to climate change"). These papers emphasize a number of factors less visible than sea ice (freshwater, sediments, organic carbon cycling) but, nonetheless, just as important especially in nearshore regions dominated by inputs from land.

A schematic diagram developed for the former publication demonstrates very nicely how the cycle of ice melt and ice freezing operate in strongly stratified vs. how it operates in more weakly stratified marine environments (Figure 10). Where the surface stratification is extremely strong, such as at the La Grande River estuary where the surface layer is nearly fresh, brine expulsion from ice formation may not be sufficient to destabilize the surface layer.

Another finding of this review and integration work was that a suite of geochemical tracers (e.g. stable isotopes, alkalinity and other water properties, organic biomarkers) greatly help provide insight into the more biogeochemical and biological (base of food web)

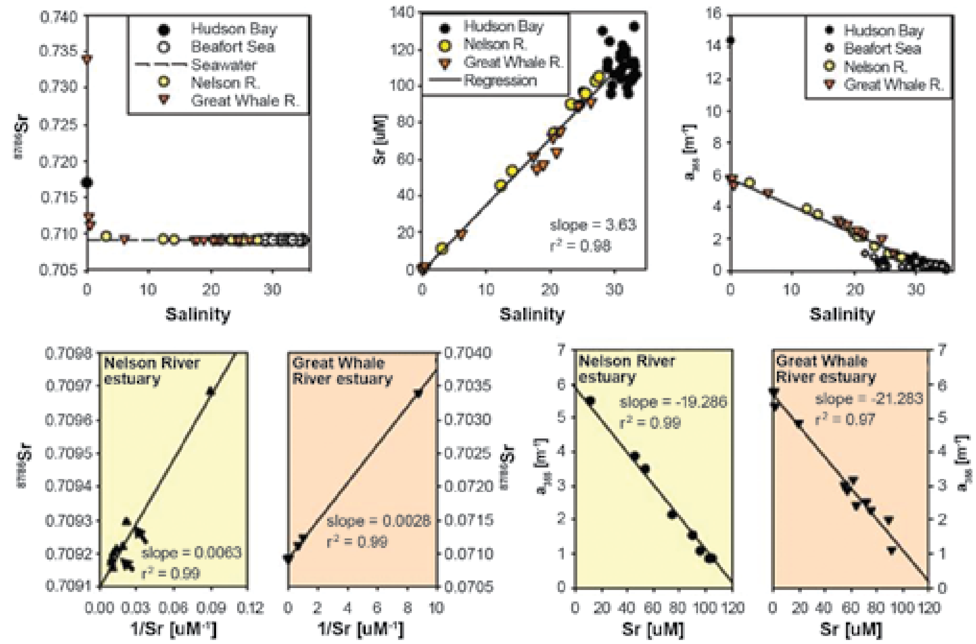

Figure 9. Dissolved Sr, $^{87/86}$Sr, and CDOM (a_{355}) in the Nelson River and Great Whale River estuaries and in Hudson Bay.

effects of environmental change (Macdonald et al., 2015a, b). Some of the most promising geochemical tracers have incorporated into the sampling program for this project already (nutrients, CDOM), and moving forward we will attempt to incorporate as many of these tracers as possible in order to capture the less-visible changes occurring in the Hudson Bay system.

DISCUSSION

Freshwater distribution, sources and interannual variability vs. change

Past field programs have focused on collecting data in Hudson Bay during the summer and fall periods, with an emphasis on areas accessible by ship (i.e., not too close to the coast), with a few notable exceptions. Winter field campaigns were conducted previously in the estuaries of the Churchill (Kuzyk et al., 2008) and Nelson Rivers (McCullough, unpub.) in western Hudson Bay, and the Great Whale River in southeast Hudson Bay (Ingram, 1981; Ingram and Larouche, 1987; Ingram et al., 1996; Legendre et al., 1996). These works have investigated the spreading of river runoff under the ice into Hudson Bay, particularly as spring freshet begins. However, there is virtually no information on how the collective inflows from distant, large-scale rivers, some now regulated (Nelson, La Grande), may affect winter conditions locally in southeast Hudson Bay. The samples and data collected in 2015 provide the first basis from which such interactions may be inferred.

The relatively low surface and subsurface (to 20-30 m) salinity in winter to the southeast of the Belcher Islands (i.e., in the coastal corridor) compared to northeast of the Belcher Islands (interior water masses) supports the notion that sufficient freshwater runoff remains in southeast Hudson Bay in winter to affect local oceanography. Indeed, river water content in January 2015 was almost twice that found in that area the previous fall (October 2014). Although tracer data have not yet been obtained from along the southeast coast of Hudson Bay, the similar (low) salinity in the upper portion of the water column southeast of

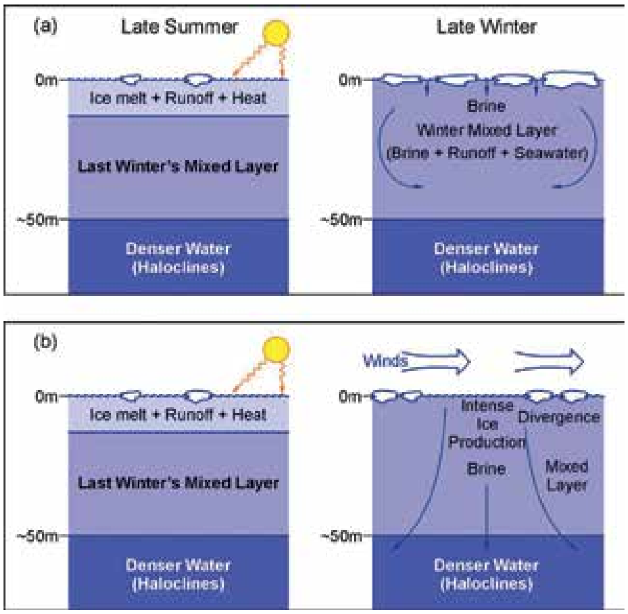

Figure 10. Schematic diagram showing how the cycle of ice melt (left) and ice freezing (right) operate in (a) a strongly stratified ocean, and (b) a more weakly-stratified system, in which ice production is sufficient to overcome the stratification and thereby export salt below the mixed layer.

the Belcher Islands and near Kuujjuaraapik suggests that river water is present in January throughout this southern coastal corridor region. Despite strong coastal currents in autumn (Saucier et al., 2004), river water clearly lingers in southeastern Hudson Bay in winter in greater quantities than during fall, and also greater than present in interior Hudson Bay water masses where circulation and exchange is slow. One question is whether this circulation has changed with river regulation, a question that we will address through modeling (in coordination with the BaySys project).

An interesting result that we do not yet fully understand is that salinity increases in coastal corridor surface waters between January and March (Figure 5), while the fractional contribution of river water also increases (to ~27%; not shown). This trend implies that other processes that add salt to the water column (i.e., sea ice formation, evaporation) during this time period must be considered. Specifically, the surface water shows an increase of ~11% brine fractional content over that January-March time period. Ongoing interpretation of the salinity-δ^{18}O record in ice cores will be focused on providing a time-series record of the surface runoff content starting at the time of ice formation and continuing to the ice sampling date as a way to check the brine inventories in the water.

Potential additional freshwater tracers

The strongly conservative behavior of Sr concentrations and isotope ratios in the Nelson River (Gueguen et al., submitted) and Great Whale River estuaries together significant differences in Sr between various estuaries (Gueguen et al., 2015) suggests that these tracers have great potential to discriminate between river waters and shelf water masses within the Hudson Bay system. The next step, commencing in January 2016, will be to test these tracers specifically in the La Grande River plume/estuary.

Biogeochemical and biological implications of changing ice/ocean conditions

The schematic contrasting the ice cycle in strongly vs. weakly stratified ocean systems (Figure 10) that we developed for our review paper (Macdonald et al., 2015a) provides essentially our conceptual model for the investigation of winter estuarine processes in the coastal corridor in southeast Hudson Bay as it relates to environmental change driven by terrigenous sources. In a highly stratified system, such as one in which winter river discharges are very high, it is expected that the freeze-melt cycle of sea ice is constrained to the winter surface mixed layer (also called polar mixed layer), which results in strong mixing in winter and stratification by sea-ice melt in summer. In contrast, in a more weakly stratified setting (e.g., low winter river discharges typical of Arctic seas), some of the salt rejected during ice formation is injected into deeper water (or the arctic haloclines). In the following summer, melt water from the ice cannot remix with the salt with the result that a more permanent stratification is produced. A third option under extremely fresh, stratified conditions (as yet unexplored in Hudson Bay or other Canadian arctic estuaries) may be failure of winter mixing. One might expect that the coastal corridor system could shift from one scenario to the other if enhanced winter river discharge from the La Grande Complex (or Nelson River) impinges on ice-forming polynyas in southeast Hudson Bay. The data generated during this project will allow us to specifically test this hypothesis.

CONCLUSION

Arctic estuarine systems are believed to be uniquely sensitive to environmental change, particularly changes in the distribution of freshwater in winter (Macdonald, 2000). Freshwater discharges that occur in proximity to flaw leads or polynyas in winter can significantly impact the rate of ice formation and its properties, deep water formation, the depth of winter mixing, and hence the replenishment of nutrients from deep layers into surface layers and ultimately biological production the following year. Predicting these impacts, however, is complicated by vertical mixing associated with tides or upwelling of deep waters due to atmospheric forcing (Dmitrenko et al., 2012).

The coastal corridor in southeast Hudson Bay is a large estuarine system, which receives freshwater from rivers in southern Hudson Bay and James Bay, as well as sea ice melt. It is also an area of numerous polynyas and thus important in terms of sea ice formation and associated processes. The amount of freshwater remaining in the coastal corridor in winter is not known but has very likely increased in recent decades as the winter river discharges associated with hydroelectric regulation have increased dramatically (in some cases as much as ten-fold). The wintertime functioning of the coastal corridor in southeast Hudson Bay may also have been impacted by climate-related changes in recent decades, such as a longer open water season in Hudson Bay.

In this project, we are collecting data to improve our understanding of how the interaction between river runoff, tidal mixing and upwelling and sea ice are modifying water masses and circulation in Hudson Bay. We are obtaining data during winter, a crucial period that has previously been neglected. We are also collecting tracer data to distinguish between different sources of freshwater in this region, and data on ice and water to provide a direct evidence of freshwater balance throughout the year. We collected preliminary data in January 2014, additional data in October 2014, and the first more comprehensive data set in January-March 2015. We initiated our second intensive period of data collection in January 2016, and will continue data collection throughout the duration of the project. Our first year's results find considerable quantities of river water in the coastal corridor in winter. It is our plan now to evaluate the interaction of this runoff with the local sea-ice formation cycle or other ocean processes. This new knowledge will provide a crucial basis for understanding the impacts of the environmental changes that are ongoing in Hudson Bay.

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

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Mapping of Arctic Canada's Seafloor: Contributions to Global Change Science, Sustainable Resource Development, Safe Navigation of the Northwest Passage, Geohazards and Arctic Sovereignty

Project Leader

Patrick Lajeunesse (Université Laval)

Network Investigators

Mark Furze (MacEwan University)
Thomas Lakeman (Norwegian Geological Survey)
Guillaume Massé (University of Plymouth)
André Rochon (Université du Québec à Rimouski)
Guillaume St-Onge (Institut des sciences de la mer de Rimouski)

Collaborators

Robbie Bennett (Natural Resources Canada - Geological Survey of Canada (Atlantic))
Steve Blasco (Natural Resources Canada - Geological Survey of Canada (Atlantic))
Calvin Campbell (Dalhousie University)
John Hughes Clarke (University of New Brunswick)
Edward King (Government of Canada - Geological Survey of Canada)
Anna Piénkowski (MacEwan University)

HQP

Etienne Brouard, Doctoral Student (Université Laval)
Myriam Caron, Doctoral Student (Université du Québec à Rimouski)
Charles De Grandpré, Doctoral Student (Université Laval)
Charles-Edouard Deschamps, Doctoral Student (Université du Québec à Rimouski)
Gabriel Joyal, Technical Staff (Université Laval)
Jean-Guy Nistad, Technical Staff (University of Hamburg)

ABSTRACT

This project undertakes the core seabed mapping component of the ArcticNet research program. Underwater acoustic mapping of the seabed relief, sediment distribution and shallow subsurface sediments are the prime datasets used by researchers to understand the geological processes shaping the seafloor, to assess geohazards and coastal habitats and to reconstruct the history of past climatic changes. These mapping results are applied to specific projects in this proposal including: (1) Marine geohazards to hydrocarbon development: Canada has potentially huge economic benefits to gain by having access to the natural resources of the Arctic Archipelago region. Exploitation in this region however, can only proceed in a safe and responsible manner, by managing the potential detrimental impacts to the environment. A key requirement is to assess potential natural hazards that might result in harmful effects both to persons and the environment. Geohazards such as submarine landslides, collapse of offshore structures built on gas-bearing seafloor sediment and the impacts of glacial and sea ice must be known and their risk managed. (2) Opening new shipping lanes and improving navigational charting: Despite previous focused mapping programs in the bottleneck regions, the Arctic Archipelago region remains sparsely mapped with shipping normally restricted to narrow singular corridors that may be ice covered. Because the CCGS *Amundsen* is operating a multipurpose mission throughout the region, there is a unique opportunity to simultaneously map uncharted regions to provide alternate pathways. (3) Past to present evolution of sea-ice regime: Understanding past climatic history is key to accurately predicting potential future ramifications of a changing sea ice regime. To responsibly plan adaptation strategies, we need to be able to predict future climatic responses and their consequences. It is also the key to understanding the nature of these changes-i.e. are they part of a natural cycle or induced by present excess of greenhouse gases? The mapping is an essential precursor to designing seabed sampling strategies to recover undisturbed sediments.

KEY MESSAGES

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

- **Northern offshore oil and gas development:** One of the major impediments to safe and environmentally responsible oil and gas development in the Canadian Arctic Archipelago is the lack of knowledge about the presence of potentially unsafe natural seabed features (so called geohazards).
- **Seabed habitat related to living resources adjacent to communities**: While the national focus in on the benefits of the non-living resource extraction, at the community level, far more reliance is placed on the ability to develop marine living resources. A first step towards this is properly delineating the submerged seabed morphology and habitats in the vicinity of those communities.
- **The need for improved charting in the North**: To undertake the scale of marine shipping required to support non-living resource programs in the north, and to ensure access for the development of coastal living resources, the state of nautical charting has to be vastly improved. The ArcticNet mapping program now represents the most extensive source of modern high density bathymetric surveying in the Canadian Arctic Archipelago.

OBJECTIVES

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

The objective of this project is to clarify the age and origin of Canada's Arctic seafloor using a multidisciplinary approach that contributes to the development of a robust geological and paleoenvironmental framework. Our specific objectives are to:

1. delimit past seafloor sedimentation patterns, including those associated with former ice sheets and ice shelves that inundated the Canadian Arctic;
2. document the modern sedimentary processes affecting the Arctic seafloor;
3. constrain previous and ongoing responses to and rates of relative sea level change;
4. generate long-term geological datasets of sea-ice, oceanographic, hydrological and ecosystem variability;
5. systematically collect new regional geotechnical observations bearing on the engineering strength and slope stability of seafloor sediments;
6. integrate knowledge of past depositional environments with regional geotechnical observations in order to develop an accurate model of regional seafloor stability, including the size, origin, timing, and environmental and economic significance of seafloor geohazards.

In line with ArcticNet's Strategic Framework, the rationale of this project is to focus on better quantifying the spatial extent and risks associated with the seabed geological hazards that are so prevalent (iceberg/icekeel scouring, fluid and gas escape structures, mass wasting phenomena and seismicity hazards).

As part of this, improved safety of navigation is an essential prerequisite to any natural resource exploitation. The CCGS *Amundsen* seabed mapping system remains Canada's best and most available asset capable of expanding safe shipping corridors in the Arctic Archipelago. She will provide our main contribution to hydrocarbon geohazard mapping in the Western Arctic.

INTRODUCTION

This project implements underway geophysical mapping programs from the CCGS *Amundsen* in support of a wide variety of Network Investigators, parallel ArcticNet projects and external partner objectives. There is continual networking activity between the group that run the mapping and other ArcticNet NIs, collaborators and external partners to ascertain the needs of the specific science programs to see how they can best be met using the capability of the *Amundsen* mapping suites.

Current foci for this program are the Beaufort Sea in the Western Arctic and the Eastern Baffin Shelf in the Eastern Arctic.

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

In the Eastern Arctic, the 2015 mapping has generated the first surveyed shipping corridors into several previously completely uncharted coastal fjords. This activity is an essential precursor to safe scientific operations in the area. The Government of Nunavut is leading a Fisheries Resource assessment program in this area and this requires the establishment of safe navigation corridors and anchorages. The same data can then be used to assess seabed habitat in support of the same program.

The continual collection of underway swath bathymetric data over 13 years of opportunistic transits and site surveys by the CCGS *Amundsen* represents the single largest holding of high density, well navigated charting information in the Arctic Archipelago. The *Amundsen* actively uses this to safely meet her science objectives. That same data has been passed on to the Canadian Hydrographic Service to update their existing chart catalogue of the Arctic Archipelago region.

A deliberate by-product of the mapping and science programs is the generation of highly qualified personnel in the fields of arctic marine geomatics and marine geology.

ACTIVITIES

In the 2015 year, the following research activities involving the training of graduate students and postdoctoral fellows were performed:

CCGS Amundsen Mapping

Leg 1 – Industry collaboration (Statoil) - Newfoundland

Research activities during this leg included (1) the installation and deployment of a tilted (30°) high-frequency sonar to map the submarine portion of icebergs (collaboration with D. Mueller), (2) the assistance for mooring deployment (collaboration with ArcticNet, Statoil, ASL) to validate water depths and determine precise mooring position, (3) continual transit mapping to increase the multibeam sonar bathymetry and sub-bottom profiler data collection (ArcticNet), (4) deployment of three transects of Moving Vessel Profiler (MVP), (5) complementary multibeam and sub-bottom profiler surveys on the Natashquan delta (Laboratoire de Géosciences Marines, U. Laval), and (6) test performance for EM302 backscatter data (J.G. Nistad).

Leg 2 – ArcticNet-Geotraces – Baffin Bay and Hudson Bay

All transits between stations were mapped with the multibeam sonar and the sub-bottom profiler. Moreover, during the non-scientific Coast Guard duty in the Hudson Bay, bathymetry data was acquired.

Leg 3 – ArcticNet – Beaufort Sea and M’Clure Strait

Additionally to the usual transit mapping, other research activities were performed: (1) landers deployment to determine proper water depth and bottom conditions (Geological Survey of Canada-GSC), (2) MVP transects in M’Clure Strait (Geotraces), (3) mooring deployment (ArcticNet), and (4) dedicated geomorphological surveys in M'Clure Strait (GSC).

Leg 4 – ArcticNet – Nares Strait and Baffin Bay

Seabed mapping was carried during transits in Eclipse Sound to increase considerably the bathymetric coverage. In collaboration with G. Massé, seafloor mapping and sub-bottom profiles were acquires to strategically select core sites (CASQ and piston cores) for paleoceanography (G. Massé) and glacial geomorphology (E. Brouard, GSC). Other surveys were performed in assistance for submerged delta coring (T. Bell, D. Forbes). Dedicated surveys were carried before ROV deployment for benthic habitat determination and seabed topography (P. Archambault, UQAR; E. Endinger, MUN). An ice island keel mapping survey was performed in Baffin Bay (D. Mueller). Finally, we performed tests offshore Iqaluit with the sonar mounted on the barge. We did not have the occasion to deploy it during the leg due to weather conditions. Those tests helped improving our ability to deploy the auxiliary launch for future Arctic high-resolution multibeam survey.

RESULTS

As always the seabed mapping results of this project act as an underlying framework for multiple research projects for NIs both within this program and others.

CCGS *Amundsen* Mapping Program: The 2015 season allowed mapping new sectors of Baffin Bay (including offshore Greenland), Baffin fjords, Nares Strait, Chukchi, Labrador and Beaufort seas (see Figure 1). These operations were undertaken by the Laboratoire de géosciences marines (U. Laval) with the participation of the Canadian Hydrographic Service. These data will allow understanding the glaciology of past ice sheet and their links with climatic events and geohazards. The newly acquired data has already been requested by more than 10 users in 2015 and is currently being used by graduate students for their thesis.

On-line Multibeam Data Management: The UNB-based multibeam data processing and on-line distribution model continued to be in service in 2015 (http://www.omg.unb.ca/Projects/Arctic/google/), but new *Amundsen* data from the 2014 and 2015 seasons were only accessible on request due to the development of a new distribution platform at U. Laval. Starting in March 2016, the newly acquired data will be integrated with the OMG database from previous years and available online on a webportal (Geoindex+; U. Laval).

Incorporation of *Amundsen* data into CHS Nautical Charts: The mapping data, generated by the *Amundsen* is delivered to the Central and Arctic region of the Canadian Hydrographic Service annually. This data is continually used for incorporation into their charting products.

DISCUSSION

Transfer of Leadership

In 2014, the Seabed Mapping Project switched lead NIs. In support of the scientific mapping needs, for the past decade, John Hughes Clarke at UNB has managed the operational mapping, the data processing and distribution, and the annual reporting. For 2014, this role passed on to Patrick Lajeunesse at U. Laval. Since 2014, *Amundsen* mapping logistics, operations, processing and dissemination has been managed by his laboratory involving Gabriel Joyal (Research Staff), Etienne Brouard (PhD student), Charles de Grandpré (PhD student) and Jean-Guy Nistad (U. Hamburg).

Dealing with Data Ownership Issues

Current Distribution Model: One of the greatest benefits of the ArcticNet Seabed Mapping Project over the past decade has been the open distribution

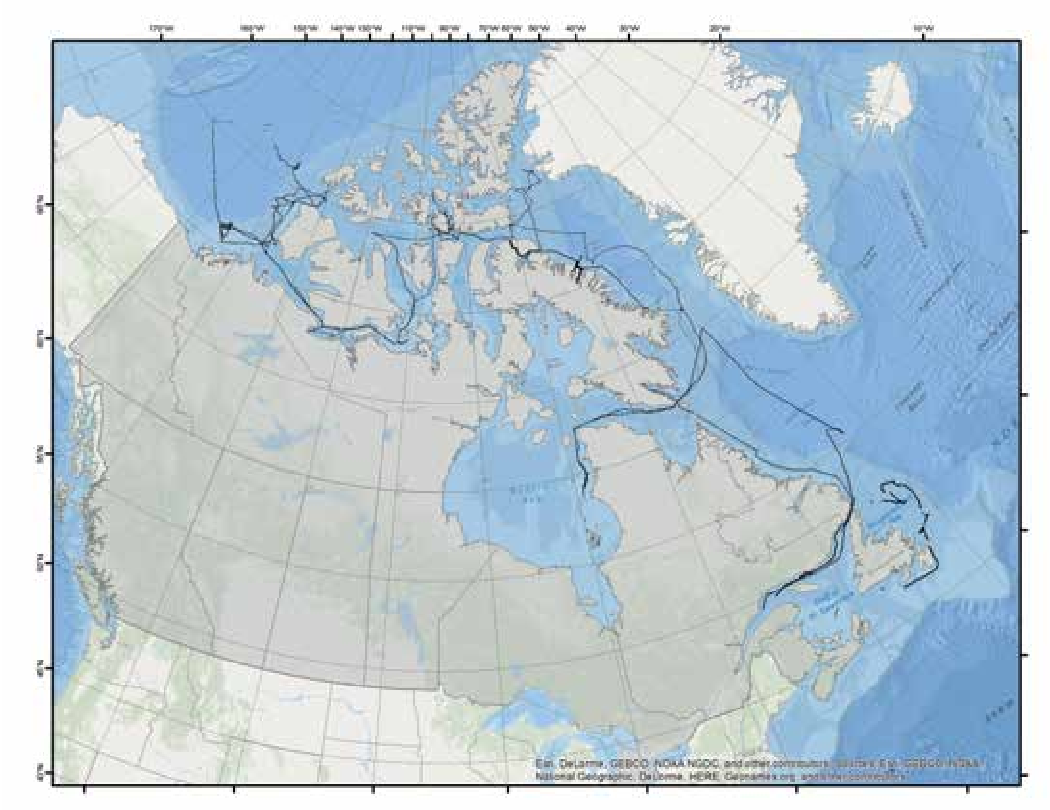

Figure 1. Shiptrack from the Amundsen expedition.

of the growing seabed mapping database. Through an internet portal, the global scientific community has been able to browse the data for the entire Canadian Arctic Archipelago at resolutions as fine as 10 m. Our greatest scientific insights into the seabed processes have come about from open availability of the serendipitous collection of transit data.

To get source data access requires just a query to UNB (merely to log usership) upon which a password was always freely given out. The data on this website did not include the 2014 data because of the transfer of the leadership of the project from John Hughes Clarke (UNB) to Patrick Lajeunesse (U. Laval). In 2015, during the construction of a new web-based data portal we handled individually all the data requests and provided the data via web transfer. The new portal will be effective in March 2016 and will be hosted on the GeoIndex+ portal (http://geoindex-plus.bibl.ulaval.ca/) of the Centre GéoStat and Library of Université Laval (see Figure 2). In 2015, we received 12 direct data request from scientists and organisations across the country (see Table 1). Many of them request (and receive) bulk downloads of the entire Arctic Archipelago dataset. At the end of 2015, we transferred all the multibeam echosounder and positioning data to the Canadian Hydrographic Service. These data will implement navigation charts in the Canadian Arctic.

Since the *Amundsen* sailed in Greenlandic waters in 2015, the bathymetric data acquired in this territory have been made available to the Greenland Government to increase their database (see CCIN)

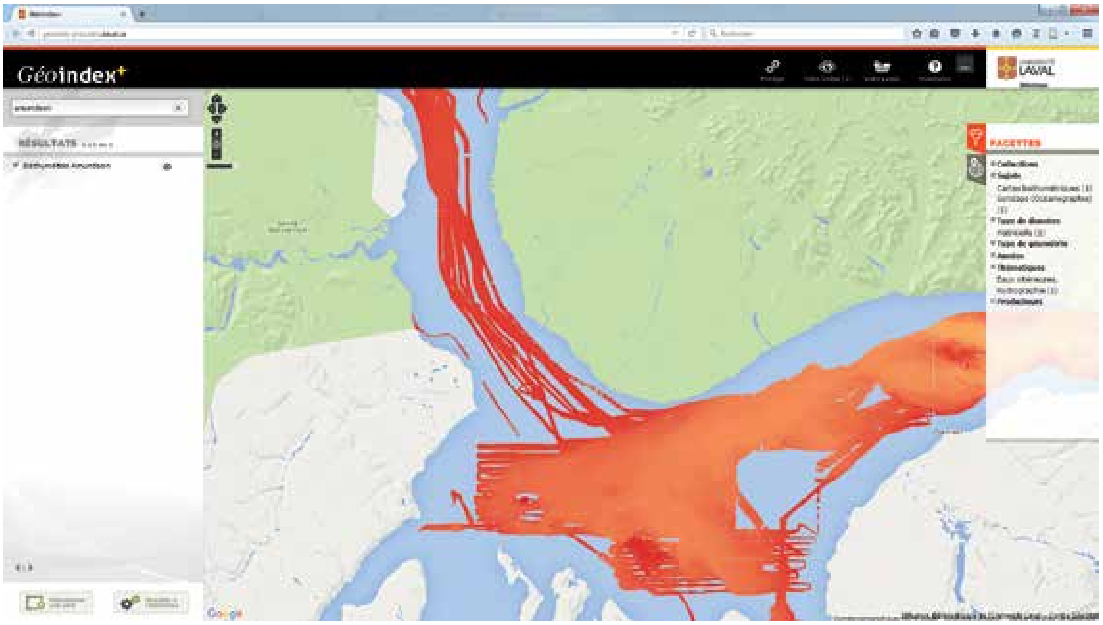

Figure 2. Example of the Geoindex Portal hosted on the GeoIndex+ portal (http://geoindex-plus.bibl.ulaval.ca/) of the Centre GéoStat and Library of Université Laval.

Historic handling of Third Party Directed Mapping: The 2009-2011 oil and gas partnership programs involved the largest financial contributions to date to ensure focused mapping (and other) programs in the Beaufort Sea. As a result, for the first time, the issue of data access was raised. It is important to emphasize that this was a partnership, not a contract. Unlike commercial contractual arrangements, just a two year delay in the posting of those datasets was agreed upon. Within that time frame, ArcticNet NIs and federal agencies (GSC, CHS) did have full access to the data. At the conclusion of the 24 month delay, however, the data went up in exactly the same free manner as all the rest.

CONCLUSION

The interest in seabed morphology extends from the shallow water need for safety of navigation to the deeper margin wherein Canada's greatest future hydrocarbon prospects lie.

Current highlights are threefold and include:

- Improved understanding of the glacial history and geohazard potential of the western arctic to promote responsible non-living resource exploitation;
- Building framework bathymetric and habitat databases in the eastern arctic to facilitate future community marine living resource exploitation; and
- Acquiring baseline bathymetric data in uncharted waters to update the nautical charting coverage, thereby improving safety of navigation across the whole Canadian Arctic Archipelago

All of these serve the underlying mandate of ArcticNet to study the impacts of climate change and modernization in the coastal Canadian Arctic. The mapping program is precisely the "development and dissemination of the knowledge needed to formulate adaptation strategies and national policies".

Table 1. Direct data request from scientists and organisations across the country.

Requests for CCGS Amundsen multibeam data in 2015

Organization	Name	Request	Raw	Processed	Date	Diffusion type	Status
M.U.N.	E. Edinger	2014 multibeam - Frobisher Bay		x	16/03/2015	Dropbox	Ended
GSC	E. King	All 2014 sub-bottom data - Canadian Arctic	x		29/10/2015	Hard drive	In progress
GSC	E. King	2015 multibeam and sub-bottom data - M'Clure Strait and Beaufort Sea	x	x	26/11/2015	Dropbox	Ended
M.U.N.	T. Bell	2015 multibeam and sub-bottom data - Merchants Bay and Frobisher Bay		x	01/11/2015	Onboard	Ended
M.U.N.	T. Bell	2014 multibeam and sub-bottom data - Merchants Bay and Frobisher Bay		x	30/11/2015	Dropbox	Ended
M.U.N.	E. Edinger	2015 multibeam and sub-bottom data - Rov dive sites and Frobisher Bay		x	01/11/2015	Onboard	Ended
Takuvik	G. Massé	2015 multibeam and sub-bottom data - CASQ sites			01/11/2015	Onboard	Ended
CHS	S. Youngblutt	2015 multibeam data; GPS; POS-MV	x	x	01/11/2015	Hard drive	Ended
Environment Canada	M. Dahl	2007-2012 multibeam data - Pangnirtung Fjord	x		04/12/2015	FTP	Ended
ArcticNet	C. Gombault	2015 multibeam data - Greenland Exclusive Economic Zone		x	18/01/2016	Dropbox	Ended
Carlton U.	D. Mueller	2015 Ice Island keel mapping data		X	01/11/2015	Onboard	Ended
LGM	P. Lajeunesse	2015 multibeam data - Baffin Fjords	x	x	01/11/2015	Hard drive	Ended

While the four highlights are our current foci, the greatest success of the program over the past decade has been the growth and open distribution of underlying knowledge about the seabed across the Canadian Arctic Archipelago and the diffusion of this new data to governmental agencies, scientists, communities and the private industry.

Acknowledgements and References sections were not provided.

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Marine Biogeochemistry and Surface Exchange of Climate Active Gases in a Changing Arctic System

Project Leaders

Tim Papakyriakou (University of Manitoba); Brent Else (University of Calgary)

Network Investigators

Maurice Levasseur (Québec-Océan)
Lisa Miller (Fisheries and Oceans Canada - Institute of Ocean Sciences)
Alfonso Mucci (McGill University)
Nadja Steiner (University of Victoria)
Helmuth Thomas (Dalhousie University)
Philippe Tortell (University of British Columbia)
Huixiang Xie (Université du Québec à Rimouski)

Collaborators

John Dacey (Woods Hole Oceanographic Institute (WHOI))
Soren Rysgaard (University of Manitoba)
Lise Lotte Sørensen (Aarhus University)
Feiyue Wang (University of Manitoba)

HQP

Mohamed Ahmed, Doctoral Student (University of Calgary)
Wieter Boone, Doctoral Student (Centre for Earth Observation Science (CEOS))
Lantao Geng, Doctoral Student (Université du Québec à Rimouski)
Margaux Gourdal, Doctoral Student (Université Laval)
Production of NO_2 and $(CH_3)_2S$ under the Arctic ice shelf
Hakase Hayashida, Doctoral Student (University of Victoria)
Eric Mortenson, Doctoral Student (University of Victoria)
Jakob Sievers, Doctoral Student (Aarhus University)
Tonya Burgers, Masters Student (University of Manitoba)
Aura Diaz, Masters Student (University of Manitoba)
Lindsay Fenwick, Masters Student (University of British Columbia)
Rachel Hussherr, Masters Student (Université Laval)
Tereza Jarnikova, Masters Student (University of British Columbia)
Jacoba Mol, Masters Student (Dalhousie University)
Jeremy Whitehead, Masters Student (University of Calgary)
Rui Zhang, Masters Student (Centre for Earth Observation Science (CEOS))
Motion correction for ship-based eddy covariance
Martine Lizotte, Research Associate (Université Laval)
Rick Raddatz, Research Associate (University of Manitoba)
Marty Davelaar, Technical Staff (Fisheries and Oceans Canada - Institute of Ocean Sciences)
Alex Hodge, Technical Staff (Sitka Scientific)
Sebastian Luque, Technical Staff (Memorial University of Newfoundland)
Cris Seaton, Technical Staff (Centre for Earth Observation Science (CEOS))
Kyle Simpson, Technical Staff (Fisheries and Oceans Canada - Institute of Ocean Sciences)
Emmelia Wiley, Technical Staff (University of Manitoba)
Neal Bailey, Undergraduate Student (Centre for Earth Observation Science (CEOS))

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

This ArcticNet project investigates four highly-coupled themes: carbon chemistry (including ocean acidification and the changing stores and distribution of inorganic carbon, including sea surface dissolved CO_2), micrometeorology (for the calculation of air-sea gas exchange and its atmospheric context), climatically active trace gases (other than CO_2, including methane - CH_4, nitrous oxide - N_2O, and dimethyl sulfide – DMS, and associated biogeochemical drivers in the marine system), and modelling (to understand how these related gases and biogeochemical processes occur over large spatial and temporal scales). In this past year, the key messages derived from published work and ongoing studies are as follows:

Carbon chemistry:

- Summertime observations of sea-surface pCO_2 (partial pressure of CO_2) within northern Baffin Bay, Nares Strait, and Lancaster Sound do not exceed atmospheric values, indicating the potential of this region to act as a sink of atmospheric CO_2. Freshwater (sea ice melt and river water) appears to be a particularly strong determinant on surface seawater pCO_2 in the region.
- Evidence that Alaskan Coastal Water (ACW), a summer Pacific water mass known to display a strong riverine signal from the Yukon River, extended to depths of ~50 m within Kennedy Channel (northern Nares Strait) during the summer of 2014. Its occurrence corresponded to very high recorded pCO_2 measurements.
- The timing and magnitude of freshwater inputs play in important role in carbon biogeochemistry and acidification in Hudson Bay, particularly in the southern portion of the water body.
- Acidification in Hudson Bay has not progressed over the five-year period between 2005 and 2010.
- Recent data indicate a relatively shallow (around 100 m) subsurface layer is likely already reaching

undersaturation with respect to aragonite[1] north of the Canadian Arctic Archipelago towards the North Pole.

- As spring Arctic sea ice matures, carbon dioxide undersaturation develops within the ice layer. Abiotic processes were dominant in modifying inorganic carbon in upper ice and early in season. Biotic processes controlled inorganic carbon in bottom ice, and late in spring season.

Micrometeorology & Flux:

- The reliable estimation of CO_2 fluxes over sea ice are often complicated by a number of issues. We have developed a method to allow for flux estimation using eddy covariance suitable for the low-flux conditions characteristic of sea ice surfaces, and which isolates local surface contribution to the flux versus its advective (non-local) component. Eddy covariance is a direct measure of the flux and is therefore preferable to other approaches.
- Frost flowers are transient crystal structures that form on new and young sea ice surfaces, and have been implicated in a variety of biological, physical and biological processes. We observed no discernable difference in surface CO_2 flux from areas populated by frost flowers versus background sea ice surface.

Climatically Active Trace Gases:

- When exposed to lower pH, phytoplankton growth and DMS production decrease linearly (pH range 8.0 to 7.2). DMS production/emission may decrease by as much as 50% if pH decreases by 0.5 units as predicted by realistic climate scenarios.

[1]Aragonite is a calcium carbonate mineral. Its saturation state (Ω_{ar}) is often used to track ocean acidification. In general, if Ω_{ar} is greater than 1, the mineral is stable, but if Ω_{ar} is less than 1, the mineral is vulnerable to dissolution (AMAP, 2013).

- Dimethylsulfide (DMS) production in melt ponds is significant and could be as high as in open waters. Hence, melt ponds represent a non-negligible source of DMS for the Arctic atmosphere when they form in spring-summer.
- Dissolved methane concentrations in surface waters of the Labrador Sea, Baffin Bay, Canadian Arctic Archipelago, and Beaufort Sea are mostly supersaturated.
- Methane concentrations in the surface water of the Parry Channel decreased from west to east.
- Many vertical profiles of methane display subsurface peaks at depths similar to those of subsurface chlorophyll *a* peaks.
- Elevated concentrations of methane are observed in bottom water of the Barrow Canyon characteristic of the Pacific winter water mass.
- Methane seepages on the Scott Inlet Shelf are confirmed with a combination of methane profiling, echo-sounder scanning, and ROV diving.
- A deep methane maximum layer is identified along the shelf south of the Scott Inlet in the Baffin Bay.
- We documented strong sources of CH_4 and N_2O to the Arctic water column over the Bering and Chuckchi Shelf regions. The high CH_4 concentrations are rapidly attenuated as waters transit towards the eastern Arctic. The accumulated N_2O persists throughout the water column all the way through to the Canadian Arctic Archipelago and Baffin Bay.
- Biological oxygen saturation (DO_2 /Ar) and pCO_2 show strongly anti-correlated distributions, reflecting a dominant signal of net community production in the mixed layer. Maximum productivity (high DO_2 /Ar and low pCO_2) appears to be centered in regions of active mixing – *i.e.* in the vicinity of hydrographic frontal zone.

- Phytoplankton assemblages proved to be quite robust to pCO_2 and light manipulations. After an initial 'light-shock' period, there were no strong effects of the manipulations on phytoplankton species assemblage composition on net primary productivity.
- Microbial degradation of DMS, DMSP, and DMSO is unlikely a major methane-producing pathway in the Canadian Arctic seas.

OBJECTIVES

This project's overarching goals are:

1. To assess climate-active gas transfer and ocean acidification in the Canadian coastal Arctic, and monitor potential climate change-effects on trace gas cycling;
2. To elucidate the underlying processes controlling the transfer of climate-active gases and ocean acidification; and
3. To forecast future gas exchange and ocean acidification, and to identify feedbacks to global climate change.

Working objectives for this past year include:

- To determine the main sources of variability in the carbonate system of seawater across the ArcticNet domain and to understand how the associated drivers change seasonally;
- To quantify the relative contribution of freshwater inputs (river, sea-ice melt, snow and glacier melt) and oceanic water masses (Pacific, Atlantic) to the vertical structure of the water column and the transfer of heat, salt and carbon between the North Pacific and North Atlantic through the Canadian Arctic Archipelago;
- To map the spatial distribution of DMS, CH_4 and N_2O across the Canadian continental shelf zone;
- To determine if melt ponds are significant sources of DMS for the Arctic atmosphere;
- To determine what processes are responsible for *in situ* DMS production and consumption in melt ponds;
- To quantify net primary productivity in surface waters based on pCO_2 drawdown and biological oxygen saturation state (DO_2 /Ar);
- To examine the influence of seawater pCO_2 variability and light intensity on primary productivity;
- To determine the biogeochemical state of remote, high Canadian Archipelago waters during late winter;
- To map the concentrations of dissolved methane and to estimate the air-sea fluxes of methane;
- To evaluate the role of water mass circulation in controlling methane distributions;
- To identify potential methane hotspots (e.g. methane seepages);
- To estimate the production and consumption rates of methane;
- To discuss some remaining ambiguities in measuring biogeochemical parameters and processes in sea ice, and make concrete recommendations for potentially useful directions for future methodological developments;
- To provide constructive guidelines to observational scientists studying sea-ice biogeochemistry toward generating new knowledge that can aid in the development of numerical models; and
- To represent the marine Arctic ecosystem through a coupled physical and biogeochemical model and, in particular to improve the representation of mechanisms that are important to the air-sea exchange of carbon and sulfur in the seasonal ice covered areas of the Arctic Ocean.

INTRODUCTION

The Earth's oceans play an important role in global cycles of climate-active gases. For example the "ocean carbon sink," offsets ~30% of annual anthropogenic CO_2 emissions (Ciais et al., 2013). 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 (Bates and Mathis, 2009; McGuire et al., 2010). Ocean uptake of anthropogenic CO_2 results in the acidification of Arctic Ocean surface waters (Steiner et al., 2014), 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). 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). N_2O is a long-lived greenhouse gas (Clerbaux et al. 2007) that is released from the ocean in high quantities, but observations in the Arctic are limited to the Greenland and Norwegian Seas (Nevison et al. 1995).

This ArcticNet Phase III project has designed to study the interactions of these climate-active gases, and aspects of ocean acidification. The project is aimed at synthesizing past results, while strategically filling remaining observational and data gaps. The project is structured around three integrated lines of investigation: (1) monitoring, (2) process studies, and (3) biogeochemical modeling.

ACTIVITIES

Ship Program: CCGS Amundsen

A portion of the 2015 ArcticNet cruise was in partnership with the Canadian GEOTRACES project. Significant synergy exists between this ArcticNet project and components of GEOTRACES' science. In total 17 berths over the cruise were dedicated to our team's objectives. Cruise participants were from Université Laval, Dalhousie, McGill, University of British Columbia and the University of Manitoba. The geographic focus of the cruise was the North West Passage of the Canadian Arctic Archipelago (CAA), Southern Beaufort Sea, Canada Basin, Baffin Bay and Nares Strait. Our team's activities onboard the *Amundsen* included:

- Measurement of dissolved CO_2 concentration in surface seawater using an automated flow through air-water CO_2 monitoring system;
- Water sampling from the ship's rosette for the determination of dissolved inorganic carbon (DIC), total alkalinity (TA), pH, $\delta^{18}O(H_2O)$, $\delta^{13}C$(DIC) and Ba at select stations;
- 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;
- Mapping the surface water concentrations of CO_2, DO_2 /Ar, and DMS using a sea-going membrane inlet mass spectrometery (MIMS). In addition, we used an automated purge and trap gas chromotograph to quantify the surface water concentrations of DMSP and DMSO (compounds related to DMS);
- Continuous underway analysis using Fast Repetition Rate Fluorometry (FRRF) was used to examine phytoplankton photosysiology in surface waters;
- FRRF analysis and ^{14}C uptake measurements in discrete samples were used to quantify primary

productivity, in relation to surface water pCO_2 and DO_2/Ar;

- Incubation experiments were conducted to examine the influence of light and CO_2 on phytoplankton C uptake;
- Concentrations of methane in surface water (5 m) and in the marine boundary layer were continuously monitored at time intervals of up to several hours along the entire cruise track;
- Vertical profiles of methane were collected at selected stations (mainly basic, full, and nutrient stations);
- Laboratory incubations were conducted to determine net production or consumption rates of methane and to assess the possibility of sulfur compounds (DMS, DMPS and DMSO) as precursors of methane using water samples collected from selected stations;
- ROV diving operations were launched during 2013 to search for potential methane seepages around stations 180 and 170 with the latter on the Scott Inlet shelf.

Ship Program: R/V Martin Bergmann

One member of our team (B. Else), and several ArcticNet students (M. Falardeau, N. Pogorzelec) participated in a one-week cruise onboard the R/V *Martin Bergmann*. Also present on the cruise were collaborators from Univeristé Laval (J-S Moore) and Fisheries and Oceans Canada (L. Harris). The study focused on the Cambridge Bay region, including Wellington Bay, Dease Strait, and Queen Maud Gulf, and included surveys along four transects, sampling near river mouths, sampling at a long-term ArcticNet monitoring station (Stn 314), recovery/re-deployment of acoustic receivers, and the installation of a land-based weather station. Samples for DIC, TA, $\delta^{18}O$ and several other parameters were collected at 12 stations. The cruise allowed us to conduct detailed investigations of melt processes, and to extend a monitoring time series that was initiated from the *Bergmann* in 2013. The cruise also complemented the 2015 *Amundsen* expedition by visiting station 315 ahead of the *Amundsen's* arrival in late August, and its return visit in late September. This sampling plan will provide a time series at this station that will be unique in its ability to measure processes from spring break-up through fall freeze-up in the western Arctic.

Ice Camp: Station Nord Research Station, Greenland

Three team members (T. Papakyriakou, S. Rysgaard, L.-L. Sørenson) and an additional two collaborating investigators (J. Ehn, B. Jensen) participated in the 2015 sea ice system experiment that operated between April and August from the Station Nord research facility in north-eastern Greenland. Team focus was air-ice-ocean CO_2 exchange in a shore fast-ice system subject to persistent and pronounced sub-glacial freshwater input from a lobe of the Greenland ice sheet. The site conditions provided a stark contrast to ice and surface conditions usually observed in the Canadian Arctic, and as such provided the opportunity to examine the influence of freshwater influx on the sea ice carbonate system, and associated air-ice flux. In Greenland our project benefited from considerable logistical and financial support through the CEOS-CERC program, and the Arctic Science Partnership with the Greenland Climate Research Centre and the University of Aarhus. Data are currently being processed by a MSc student (Wickström).

Ice Camp: Green Edge

Several members of our team participated in the 2015 Green Edge campaign, near to Qikiqtarjuaq on Baffin Island. Water column samples were collected for DIC and TA analysis throughout the late winter to early summer season, and the change in the biology and DMS dynamics in melt ponds were also studied.

Ice Camp: Cambridge Bay & Ocean Networks Canada Observatory

We have deployed a number of CO_2 system sensors on the Ocean Networks Canada observatory in Cambridge

Bay. In addition to providing a means to monitor changes in the CO_2 system at that location through the winter, the deployment is also serving to assess the behaviour of the sensors, thanks to discrete samples being collected adjacent to the observatory by the staff of the Canadian High Arctic Research Station. A SAMI pH sensor, a prototype Aanderaa pCO_2 optode, and a Pro-Oceanus CO_2 sensor were deployed in August and the data are available on the web in real-time.

Other Campaigns

Team members (McGill) also participated (MSM46; August 26-September 24, 2015) in a German-lead (University of Hamburg) 4-week research cruise on the R/V *Maria S. Merian*. The team recovered 400 samples for $\delta^{18}O(H_2O)$ and $\delta^{13}C(DIC)$ from the eastern St. Lawrence Estuary, the Belles-Isles Strait, the Labrador Shelf, the Labrador Sea and Baffin Bay, linking up with the Geotraces/ ArcticNet transect in the Labrador Sea and Baffin Bay.

Sea Ice and Ocean Modelling

This year, our efforts focused on developing a 1D model tool that includes a physically driven sea ice module as well as a sympagic (in, or attached under, the sea ice) algae population that is coupled to an under-ice pelagic community. The simulated ice algal growth and loss are based on Lavoie et al. (2005), and are limited by light, ice growth/melt, and two nutrients (silicate and nitrate). The pelagic ecosystem contains two phytoplankton and two zooplankton species as well as three nutrients (silicate, nitrate, and ammonium). The model contains carbon and DMS modules (incorporated into the model by students). Model results were compared with field measurements (ArcticNet) made near Resolute Bay in the CAA, during two field campaigns in 2010 and 2011 (for carbon: Geilfus et al., 2014, Brown et al., 2015; for sulfur: Galindo et al., 2014), and the model results agree well with observations. In parallel, the development of the Arctic regional model within DFO and EC has been progressing and the model has been included in a recent model inter-comparison analyzing the evolution of the subsurface chlorophyll maximum (SCM) in the Canada Basin, and the ratio of surface to integrated Chl-a in a future climate scenario (Steiner et al. 2015).

RESULTS

Select results are organized under the sub-headings: carbon chemistry, micrometeorology, trace gases, and modeling. Results reported here include preliminary results associated with the recent field programs, and research that has made its way into peer-reviewed literature this reporting year from previous experiments.

Carbon Chemistry

i) Implications of a Changing Arctic on Summertime Rates of Air-Sea CO_2 Exchange within the Eastern Canadian Arctic (Burgers, 2015; Burgers et al., in progess)

Waters within the eastern Canadian Arctic were found to be consistently undersaturated in CO_2 throughout the summer season (Figure 1). The entire region acted as a sink of atmospheric CO_2, with average uptake rates of -6.6 and -5.2 mmol C m^{-2} d^{-1} in 2013 and 2014 respectively. High concentrations of sea ice melt were identified in proximity to melting ice floes in Barrow Strait, as well as throughout the surface mixed layer of eastern Baffin Bay. Regions displaying high fractions of sea ice melt consistently coincided with areas of low pCO_2. During 2014 significant fractions of river runoff were found within Kennedy Channel (northern Nares Strait) extending to depths of ~50 m. Salinity and chemical characteristics of this water match with the description of Alaskan Coastal Water (ACW). Our highest recorded pCO_2 measurements coincide with the location of the ACW (Figure 1). Biology was found to play a minor role during summer in both years, with low chlorophyll-α concentrations ubiquitous throughout the region's surface waters.

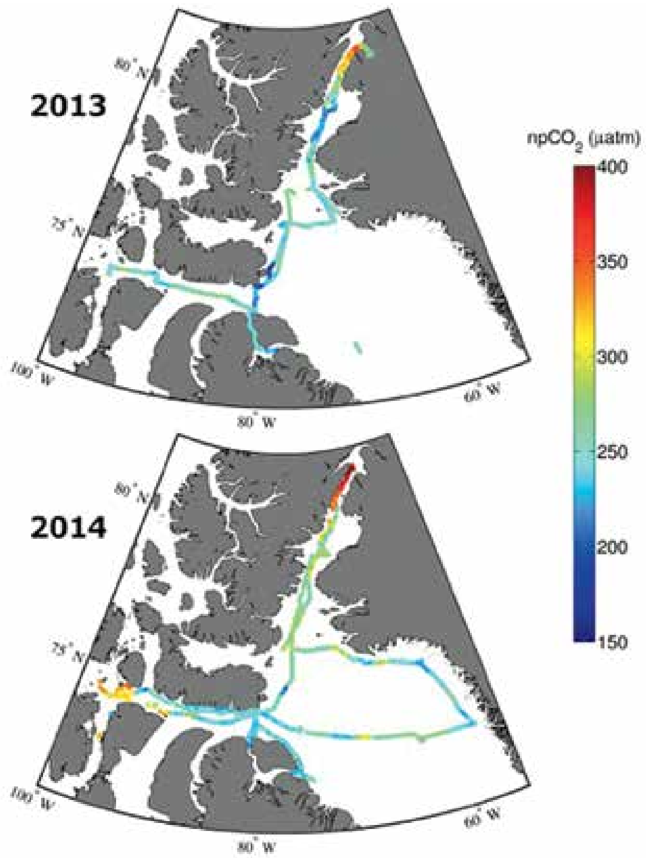

Figure 1. Variations in npCO$_2$sw (temperature-normalized pCO$_2$sw) throughout the eastern Canadian Arctic during summer of 2013 and 2014.

ii) Inorganic Carbon Cycling and Biogeochemical Processes in an Arctic Inland Sea (Hudson Bay) (Burt et al., in progress)

A recent analysis of data associated with the 2010 *Amundsen* cruise in Hudson Bay shows the surface distributions of carbon system parameters within the Bay (Figure 2) are strongly influenced by freshwater (river and sea ice melt), particularly on the southern and eastern sides of the Bay. Distributions of TA (Figure 2b), DIC (Figure 2c), and Ω_{Ar} (Figure 2d) mimic that of salinity (Figure 2a), with maxima in the high salinity waters of the Hudson and Foxe Channels, and minima along the southern coast of Hudson Bay. One notable exception however, is near the Nelson River, where stations exhibit low salinities

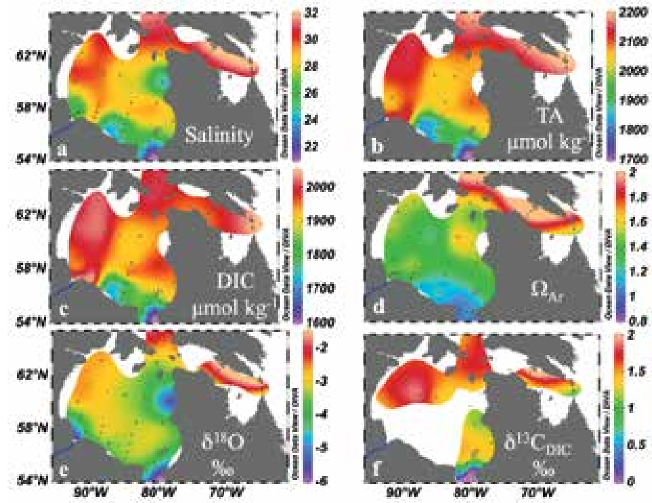

Figure 2. Surface distributions of salinity (a), TA (b), DIC (c), Ω_{Ar} (d), $\delta^{18}O$ (e), and $d^{13}CDIC$ (f). Nelson River is shown (blue line).

but relatively high DIC, TA and Ω_{Ar}. The high salinity water in northwestern Hudson Bay represents water recently introduced from the Foxe and Hudson Straits, with salinities generally decreasing in a counterclockwise fashion due to freshwater influence. At the mouth of James Bay, the salinity and carbonate parameters are higher on the western edge, where waters enter the bay, compared to the eastern edge, where waters altered by large James Bay rivers exit back into Hudson Bay.

iii) Late winter biogeochemical conditions under sea ice in the Canadian High Arctic (Findlay et al., 2015)

The Catlin Explorer Transect (CET) crossed the Makarov Basin (water depth >1000 m), over the Lomonosov Ridge, and into the Amundsen Basin (water depth >4000 m), thus crossing Pacific-influenced water masses, similar to those expected to enter the Canadian Arctic Archipelago near the Catlin Ice Base (CIB) and exemplified by the phosphate-nitrate relationship along the CET.

The $CaCO_3$ saturation states (calcite and aragonite) in the surface waters across the whole transect (not shown) were, in general, lower than previously observed spring and summer surface water conditions for other areas of the Arctic Ocean. Although different drivers are likely to contribute to these low wintertime pH and saturation state conditions than drivers in more southerly locations, these data confirm the hypothesis that winter pH and saturation states in surface waters will be lower than those during the productive summer and spring seasons. The CET data set provides spatial evidence that moving offshore towards the central Arctic, late winter aragonite saturation states in the surface layers are <1.5 and beyond 88.5°N actually decrease in the surface 10 m to ca. 1.2; pH also decreases from approximately 8.15 between 86 and 88.5°N to 8.05 at the North Pole. Together with profile data from the CIB, the CET data suggest that the relatively shallow (around 100 m) subsurface layers are likely already reaching undersaturation with respect to aragonite. Any upwelling events or internal mixing that drives this water onto the slopes and shelves would mean benthic communities there could already be exposed to year-round corrosive conditions.

Low NO_3^-:PO_4 but high Si:NO_3^- in the surface waters (not shown) indicated that this region was nutrient-depleted and consequently even as light increases in spring, primary production could remain nutrient-limited in this region.

iv) Inorganic carbon system dynamics in landfast arctic sea ice during the early-melt period (Brown et al., 2015)

Observations over a six-week time series of landfast sea ice in Resolute Passage captured an important transition over the early-melt period. We observed a spatial and temporal segregation between the dominant processes controlling CO_2 within the ice, distinguishing the bottom ice, the middle ice column, and the upper ice/ice-atmosphere interface into separate biogeochemical zones, despite the high connectivity of the brine system in the warming ice (Figure 3). Our time series illustrated that pCO_2 within the ice was strongly controlled by physical processes associated with warming. During the early warming period, sea ice melt dilution exerted a substantial influence on pCO_2 within the majority of the ice column, except in the bottom ice, where biological DIC uptake maintained undersaturated pCO_2 conditions throughout the time series. Our observations suggest that 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. Aside from CO_2 drawdown by photosynthetic algae in the bottom 3 to 10 cm of ice, brine pCO_2 in the majority of the ice column is controlled by solubility. Thus, the only net change in inorganic carbon inventory over the transition from winter to spring is associated with a small uptake of CO_2 due to $CaCO_3$ dissolution, likely balancing CO_2 redistribution during $CaCO_3$ formation in early winter.

Trace Gases

i) Melt ponds as a source of CMS for the Arctic atmosphere (Gourdal et al., in progress)

DMS concentrations shown in Figure 4 illustrates the relationship between DMS concentrations and the salinity of the melt ponds. DMS concentrations range from 0 to 14 nmol l-1 while values of salinity spread from 0 to 8.5. DMS levels in freshwater melt ponds were consistently non-detectable. In situ DMS production seems to occur only in brackish melt ponds. The predominant process proposed for melt ponds salinization is seawater intrusions through low free-boarded permeable sea ice.

Daily DMS budget incubations were conducted with melt pond water from the 2014 CCGS *Amundsen* cruise, and in proximity to Broughton Island in 2015 to identify and quantify the processes responsible for in situ DMS production and consumption. Amendments with the stable isotopes ^{6}H-Dimethylsulfoniopropionate (6H-DMSP) and ^{13}C-Dimethylsulfoxide (^{13}C-DMSO) allowed the discrimination of two major DMS-producing pathways: DMSP biological cleavage and DMSO biological reduction. Examples of results are presented in Figures 5 (freshwater melt pond) and 6 (brackish

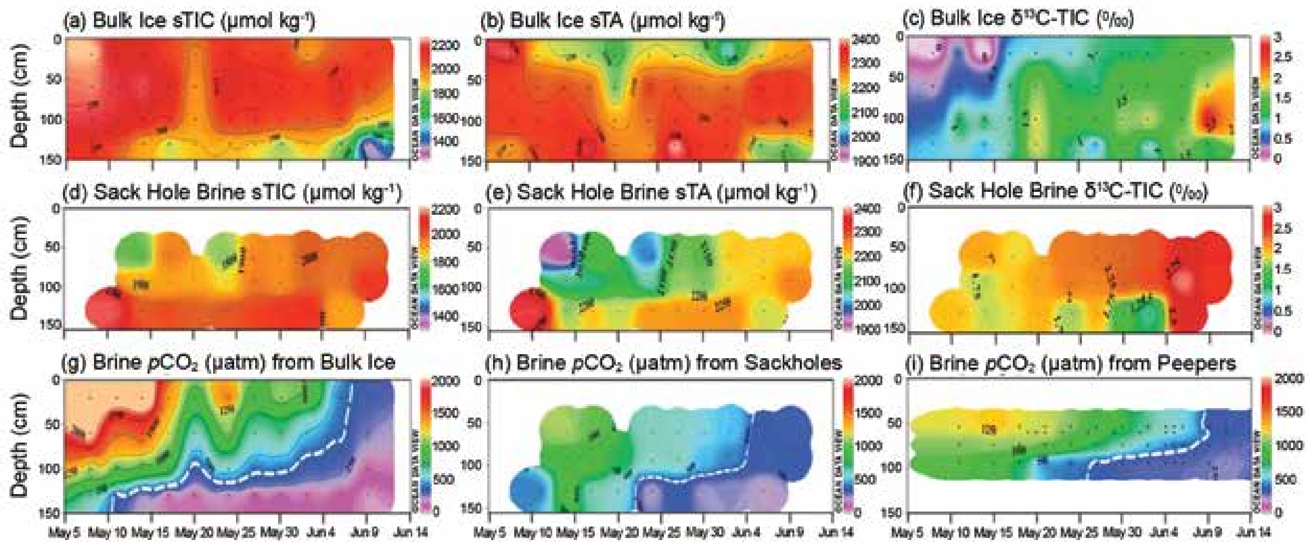

Figure 3. Six week time series of carbonate system parameters in sea ice and sackhole brine samples. Prefix "s" denotes TA and TIC data were normalized to a salinity of 32.5, the average S of under-ice surface seawater. (a) Bulk ice sTIC; (b) bulk ice sTA; (c) bulk ice δ^{13}C-TIC; (d) sackhole brine sTIC; (e) sackhole brine sTA; (f) sackhole brine δ^{13}C-TIC; (g) brine pCO_2 as calculated from bulk ice TA and TIC.

melt pond). Freshwater melt ponds show no DMS production during the 24 h incubation experiments, even when DMSP and DMSO, two precursors of DMS, are added. The absence of DMS production may be explained by the extremely low bacterial biomass characterising these melt ponds (Michel Gosselin, pers. comm.). Hence, freshwater melt ponds appear to be "pristine" environments lacking the biological potential for DMS production.

In contrast to the freshwater melt ponds, DMS is generally present in brackish melt ponds and DMS production could be enhanced when adding DMSP and DMSO (Figure 6). Results from the 6H-DMSP and ^{13}C-DMSO treatments show that bacterial DMSP degradation is the main source of DMS in these melt ponds (Figure 7). Finally, the comparison between the light and dark treatments shows that photo-oxidation, along with ventilation, is a major sink for DMS in brackish melt ponds.

ii) Impact of ocean acidification and light on DMS production by Arctic marginal ice blooms (Hussherr et al., in progress)

Bioassay incubations of 10 days were conducted in Northern Baffin Bay during the summer of 2015 in order to simulate conditions encountered by blooming phytoplankton in a progressively acidified Arctic Ocean (six levels of decreasing pH) submitted to light fields typical of those encountered under the ice pack (low-light; simulation of an under-ice bloom) and in open waters (high-light; simulation of a marginal ice bloom). Results show that the different light regimes had no significant impact on the development of the phytoplankton bloom and on DMS net production (Figures 8a,b). Phytoplankton net growth was not affected by a decrease in pH between 7.91 and 7.61, but decreased linearly for pH below 7.61. The decreases in pH were accompanied by linear decreases in DMS concentrations over the whole range of acidification increments tested. These results indicate 1) that the different light regimes to which under-ice and marginal ice blooms are exposed have no or little effect on algal net growth and DMS net production, and 2) that DMS

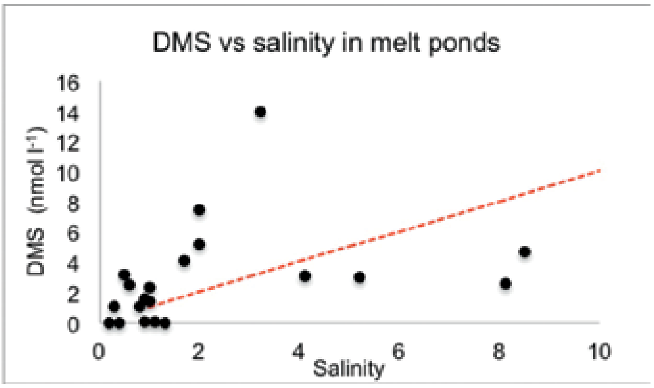

Figure 4. Relationship between DMS concentrations and salinity for 23 Arctic melt ponds sampled over three years. The dotted line indicates the theoretical one to one relationship between DMS and salinity.

net production is negatively impacted by OA. Predicted decreases in pH in Arctic waters could results in a 50% decrease in DMS net production by under-ice and marginal ice blooms.

iii) Methane observations in the Canadian Arctic (Xie et al., in progress)

Surface waters in all sampling areas were mostly oversaturated with methane (Figure 9), thereby acting as a source of atmospheric methane. Surface-water methane concentrations in the Parry Channel decreased from west to east. Five types of methane vertical profiles were obtained: 1) surface enrichment (Figure 10a), 2) mid-depth minima (Figure 10b), 3) subsurface peaks (Figure 10c), 4) deep-depth maxima (Figure 10d), and 5) bottom enrichment (Figure 10e). ROV diving operations demonstrated that the bottom enrichment observed in the Scott Inlet shelf water was due to active methane seepages in that area. It is suggested that the deep methane anomaly detected at station 180 could have resulted from advection of methane from nearby hydrocarbon seeps.

Results from laboratory incubations indicate that the turnover time of methane in the western Baffin Bay shelf water ranged from 170 to 870 d, and that microbial degradation of DMS, DMSP, and DMSO was unlikely a major pathway for methane production in the study area.

iv) Methane and nitrous oxide observations in the Canadian Arctic (Fenwick and Tortell, in progress)

Strong sources of CH_4 and N_2O to the Arctic water column were observed during the 2015 *Amundsen* cruise over the Bering and Chuckchi Shelf regions. The N_2O source is derived primarily from denitrification, based on the tight correlation between NO_3- deficit (N*) and N_2O accumulation. The accumulated N_2O persists throughout the water column all the way through to the Canadian Arctic Archipelago and Baffin Bay (Figure 11a). High CH_4 concentrations are likely associated with sedimentary sources include potential clathrate deposits. Unlike N_2O, the high CH_4 concentrations are rapidly attenuated as waters transit towards the eastern Arctic (Figure 11b).

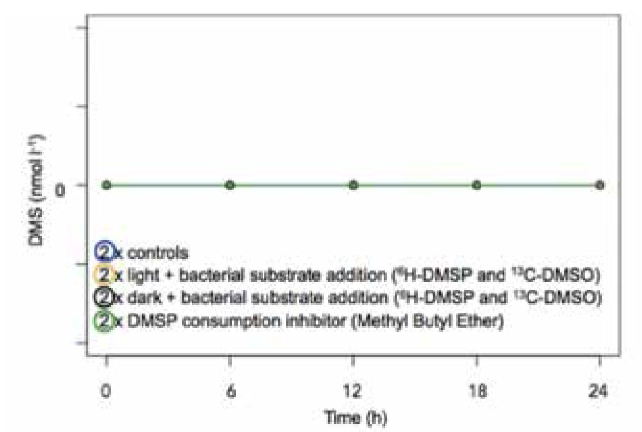

Figure 5. DMS incubation of a freshwater melt pond during the joint ArcticNet/Netcare campaign in 2014. The DMS concentrations are plotted over 24 h for the four different treatments are listed in the legend.

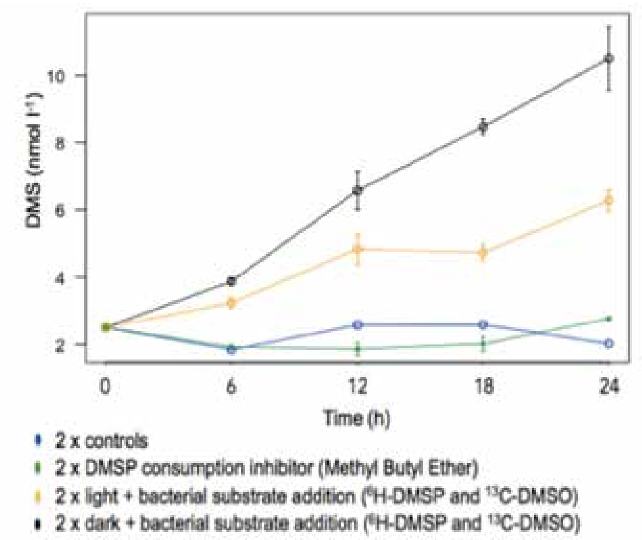

Figure 6. DMS incubation of a brackish (salinity of 8.1) melt pond during the joint ArcticNet/Netcare campaign in 2014. The DMS concentrations are plotted over 24 h for the four different treatments are listed in the legend.

Modelling

i) Biogeochemical modelling (Steiner et al., in progress)

As part of the project, we are developing is 1D model tool which includes a physically driven sea ice component as well as a sympagic (in, or attached under, the sea ice) algae population coupled to an under-ice pelagic community. The simulated ice algal growth and loss are based on Lavoie et al. (2005), and are limited by light, ice growth/melt, and two nutrients (silicate and nitrate). The pelagic ecosystem contains two phytoplankton and two zooplankton species as well as three nutrients (silicate, nitrate, and ammonium). The model contains carbon and DMS modules (incorporated into the model by students Eric Mortenson and Hakase Hayashida, respectively). Model results are compared with field measurements made near Resolute Bay in the CAA, during two field campaigns in 2010 and 2011 (for carbon: Geilfus et al., 2014, Brown et al., 2015; for sulfur, Galindo et al., 2014), and the model results agree well with observations. Sensitivity analyses have been performed for parameters involved in photosynthetic efficiency of ice algae, affecting the magnitude of

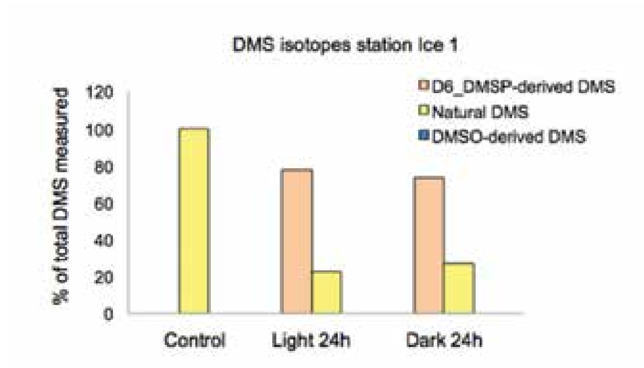

Figure 7. Identification of the sources of the DMS produced during brackish melt pond incubations using a DMS double ionization mass spectrometry (GC/MS-MS) technique.

the bloom, and for different functional forms for the mortality term (quadratic and linear forms), which affect the timing and magnitude of the bloom.

In parallel the development of the Arctic regional model within DFO and EC has been progressing and the model has been included in a recent model inter-comparison analyzing the evolution of the subsurface chlorophyll maximum (SCM) in the Canada Basin and the ratio of surface to integrated Chl-α in a future climate scenario (Steiner et al. 2015). Observations show a deepening of the SCM before 2010 and stabilizing values in recent years, suggesting an unclear future trend. However, most models indicate a continuation of the observed deepening of the SCM following a deepening of the nitracline until the models reach a new state with seasonal ice-free waters. However, a variety of reasons cause discrepancies among the models. Intermodel differences in the representation of a SCM in the Canada Basin are mainly due to biogeochemical factors: (1) inconsistencies in nutrient availability and (2) differences in the represented ecosystem community structure. On the other hand, intermodel differences in the projected deepening of the SCM in the Canada Basin are likely caused by a variety of physical factors: (1) the different rate of recent and projected sea ice retreat affecting freshwater contribution and stratification, (2) the model's strength of the Beaufort Gyre circulation and consequent accumulation of freshwater in the Canada Basin, and (3)

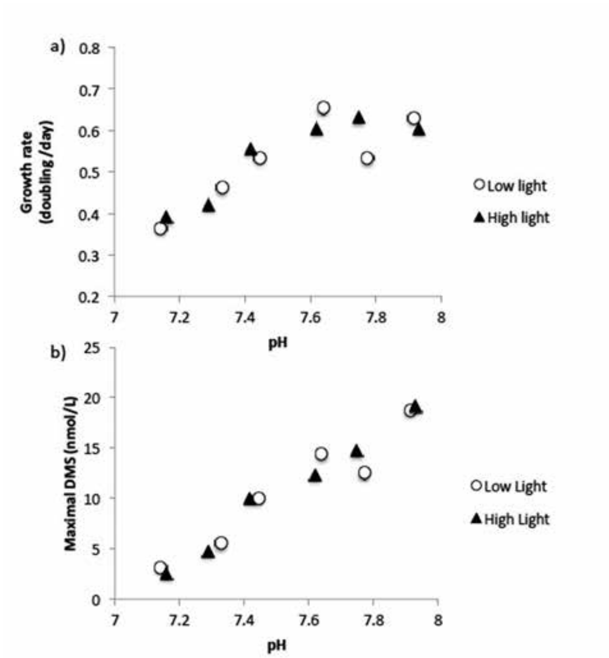

Figure 8. Relationship between variations in pH (total range of acidification increments) and a) phytoplankton growth rate and b) maximal DMS concentration during an acidification experiment under two light intensities conducted in Baffin Bay, Arctic Ocean (summer 2015).

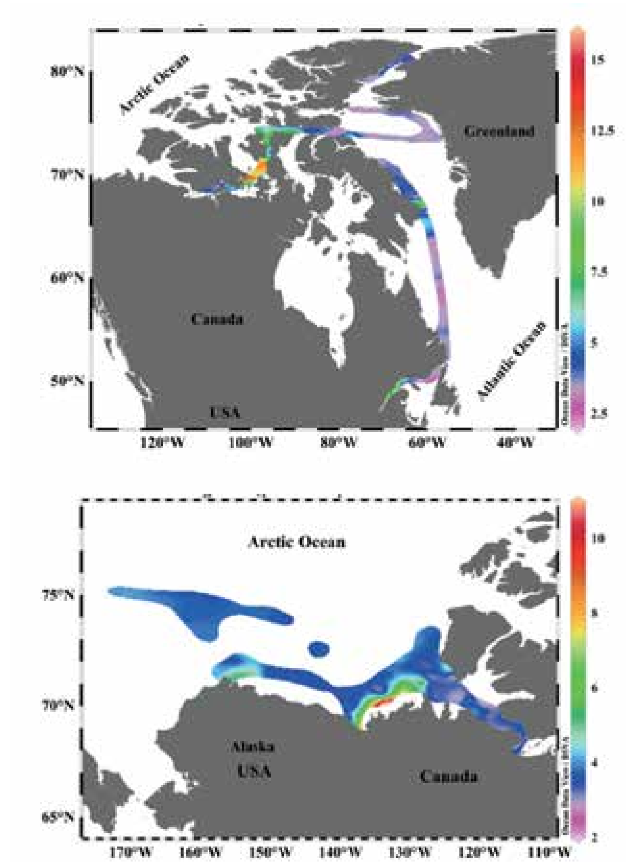

Figure 9. Methane concentrations (nmol L^{-1}) in surface waters (≤ 5 m).

differences in horizontal water mass transport, possibly related to vertical resolution on the shelves. The ratio of near-surface Chl-α to the depth-integrated Chl-α is projected to decrease in most areas of the Arctic Ocean, indicating an enhanced contribution of subsurface Chl-α. Exceptions are some shelf areas and situations when the ice cover thins enough to permanently break the stratification and allow nutrient mixing into the near-surface ocean.

DISCUSSION

Collectively our work demonstrates the use of powerful autonomous monitoring technologies, and discrete sampling to understand biogeochemical processes in Arctic waters. Results from observational studies inform our modeling inititatives. In the following results are discussed by theme.

Carbon Chemistry

Freshwater in the marine system has a major influence on the summertime surface pCO_2 variations reported by Burgers (2015) in Baffin Bay and Nares Strait. Startling was the observation on the effect of the ACW on pCO_2 in Nares Strait. The ACW must be transported great distances from its origin in the Bering Sea in order to reach the waters of Nares Strait. Circulation patterns of ACW have been linked to surface wind fields and the phase of the Arctic Oscillation (AO), with strongly positive AO periods leading to the transport of ACW north of Ellesmere Island (Steele et al., 2004). Using monthly mean AO indices from the NOAA Climate Prediction Center we found AO indices within early (JFM) 2014 to be positive, whereas in early 2013 AO indices were negative.

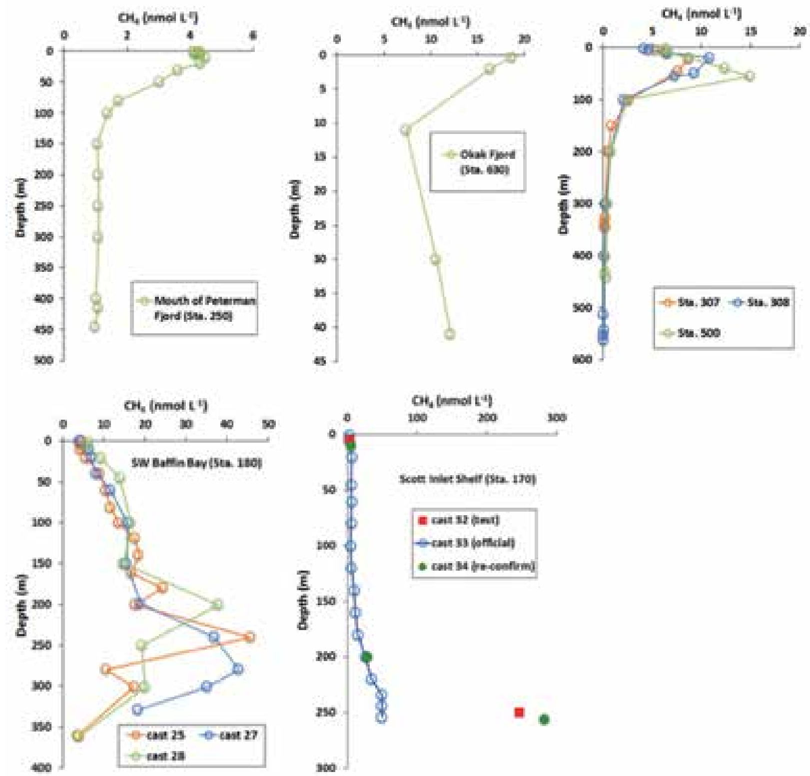

Figure 10. Typical vertical profiles of methane characterized by surface enrichment (a), mid-depth minima (b), subsurface peaks (c), deep-depth maxima (d), and bottom enrichment (e).

This positive AO period in early 2014 may have contributed to the increased transport of ACW into Nares Strait, linking pCO_2, and hence air-sea exchange to atmospheric modes of circulation.

The surface distributions of carbonate parameters reported by Burt et al. (in progress) throughout Hudson Bay in 2010 are similar to those reported by Azetsu-Scott et al. (2014) for the Bay in September, 2005. Concentrations within Hudson Strait and Foxe Channel are comparable, and the north-south gradient in properties within Hudson Strait is apparent in both studies. Aragonite saturation (Ω_{Ar}) in surface waters show no significant differences between 2005 and 2010, with surface waters nearing the saturation limit at the mouth of James Bay in both years. However, subtle differences do exist between these datasets that we attribute to the seasonal timing of sample collection and general circulation patterns.

The study reports the alkalinity of rivers entering the Bay vary both regionally and with small changes in near-surface depths. The latter highlighting the importance of careful surface water sampling in highly stratified waters.

Observations by Brown et al. (2015) reveal a surprisingly dynamic carbon system within the sea ice, even before the snow had melted from the ice surface. Vertical segregation of abiotic and biotic processes during the early melt period create a heterogeneous, environment in the sea ice where the lower portion of the ice column becomes sufficiently permeable and illuminated thereby supporting rapidly growing autotrophic communities (algae), while the upper portion of the ice remains dominated by the physical constraints characterizing the late winter sea-ice system. Reduction of snow cover and the transition to a completely isothermal ice column mark the end of

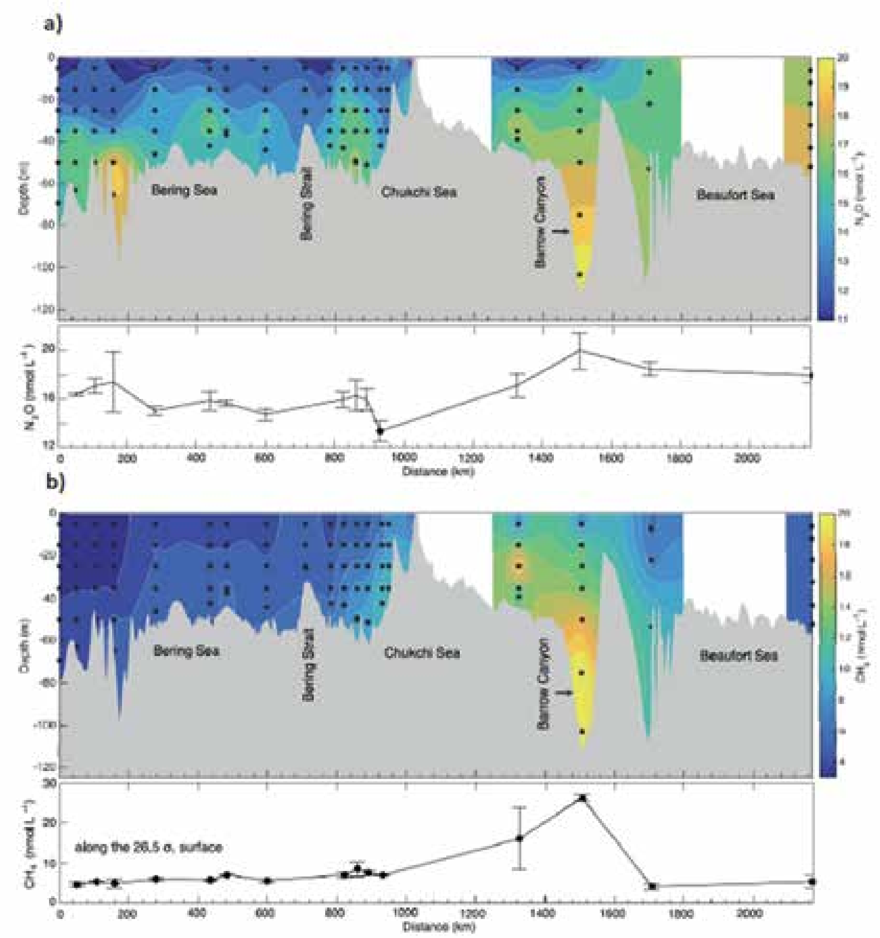

Figure 11. Cross section of dissolved (a) N_2O and (b) CH_4 across the western sector of the 2015 Amundsen cruise path (Fenwick, MSc thesis in progress). σ in the figures is specific gravity of seawater.

the early melt period and drive the ice column towards pCO_2 under-saturation, contributing to a weak CO_2 sink as melt advances.

The results suggest the impact of sea ice melt on the seasonal surface ocean CO_2 sink in the Arctic Ocean may be small, and that regional differences in the surface water inorganic carbon inventory may play a more significant role in determining the net effect of sea ice melt on the air-sea CO_2 flux. Through field studies we seek evidence supporting the presence of a pronounced sea ice carbonate pump. These results indicate that drainage of brines with low TA:TIC ratios, such as those we observed, triggered by early-spring warming would be an ineffective seasonal sea-ice carbonate pump, as early season brine TA:TIC differed only marginally from surface seawater in our study area.

Modeling

The results (Steiner et al., 2015) confirm that production algorithms determining vertically integrated Chl-α from near-surface Chl-α need to represent the characteristic SCM in the Arctic, but at this point it is not suggested that algorithms need to be further adjusted to properly represent enhanced subsurface production in the future. Improving the nutrient data base in the Arctic is a major step in supporting the biogeochemical model development.

In a separate work, Steiner et al. (submitted) articulate the need for close collaboration between modellers and observational scientists. In short, ideal observations in support of sea-ice biogeochemical model development should be:

1. Multidisciplinary: physical, biological, and chemical properties should be measured at the same time and the same place to understand causes, effects, and feedbacks;
2. Comprehensive: all of the ecological domains (atmospheric, cryospheric, pelagic, and benthic) should be measured when possible, to link them and understand the fluxes between them;
3. Spatially and temporally extensive: long time series that span ice formation, ice melt, and the open water season, preferably over a reasonable spatial extent, are needed for a holistic understanding; and
4. Quantitative: moving from conceptual to numerical models requires quantification of processes and rates.

The list can be shortened considerably if modellers and observers work together from the onset of a program to focus on common hypotheses. In such a case, rather than asking how observations can improve models, such partnerships would be aiming at combining (even imperfect) models with (very restricted) measurements to improve our understanding of specific processes.

CONCLUSION

Freshwater inputs are shown to play a major role in influencing summertime variations in the carbon system parameters of surface seawater in both Baffin Bay and Hudson Bay. Areas of significant sea ice melt (Barrow Strait and eastern Baffin Bay) were found to coincide with the lowest seawater pCO_2 measurements, whereas areas of riverine input was found to increase seawater pCO_2. In Hudson Bay the parameters mimic the distribution of salinity, except near large rivers like the Nelson River.

On warming the sea ice within the CAA could be separated into distinct geochemical zones where biotic and abiotic processes exerted different influences on inorganic carbon and pCO_2 distributions. Both $CaCO_3$ dissolution and seawater mixing were found to contribute alkalinity and dissolved inorganic carbon to brines, with the $CaCO_3$ contribution driving brine pCO_2 to values lower than predicted from melt-water dilution alone. This work reveals a dynamic carbon system within the rapidly warming sea ice, prior to snow melt. We suggest that the early spring period drives the ice column towards pCO_2 undersaturation, contributing to a weak atmospheric CO_2 sink as the melt period advances.

The outer shelf and slope region north of the Canadian Archipelago is dominated by a mix of land-fast ice and pack ice, first- and multi-year ice, with polynyas, flaw leads, and open ice areas, which create new (first-year) ice. In these regions the wintertime surface mixed layer was characterized by low DIC and total alkalinity concentrations, resulting in waters undersaturated with respect to pCO_2 (285 µatm) with a surface water pH of 8.14 and Ω_{Ar} = 1.36. pCO_2 increased with depth to a maximum of 476 µatm at 100 m, resulting in a pH of 7.95, and an aragonite Ω_{Ar} = 1.03. The $CaCO_3$ saturation states (calcite and aragonite) in the surface waters across the whole transect were, in general, lower than previously observed spring and summer surface water conditions for other areas of the Arctic Ocean.

The production and emission of trace gases (CH_4 and N_2O) is dynamic, showing pronounced variation across the ArcticNet domain. Surface waters appear oversaturated in CH_4.

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Arctic Geomicrobiology and Climate Change

Project Leader

Soren Rysgaard (University of Manitoba)

Network Investigators

Jens Ehn (University of Manitoba)
Brent Else (University of Manitoba)
Pierre Francus (Institut national de la recherche scientifique - Eau, Terre et Environnement)
Ryan Galley (University of Manitoba)
Monika Pucko (University of Manitoba)

Collaborators

David Babb (University of Manitoba)
David G. Barber (University of Manitoba)
Igor Dmitrenko (University of Manitoba)
Nicolas Geilfus (University of Manitoba)
Ronnie Glud (University of Southern Denmark)
Yu-Bin Hu (University of Manitoba)
Casey Hubert (University of Manitoba)
John Iacozza (University of Manitoba)
Liisa Jantunen (Environment Canada - Science and Technology Branch)
Sergei Kirillov (Arctic and Antarctic Research Institute)
CJ (Christopher John) Mundy (Université du Québec à Rimouski)
Masayo Ogi (University of Manitoba)
Tim N. Papakyriakou (University of Manitoba)
Gary A. Stern (University of Manitoba)
Feiyue Wang (University of Manitoba)

HQP

Wieter Boone, Doctoral Student (Centre for Earth Observation Science (CEOS))
Karley Campbell, Doctoral Student (University of Manitoba)
Ice algal blooms in Resolute Passage
Odile Crabeck, Doctoral Student (University of Manitoba)
Sea ice biogeochemistry and air-ice gas fluxes
Heather Kyle, Masters Student (University of Manitoba)
Virginie Galindo, Post-Doctoral Fellow (Université Laval)
Marcos Lemes, Research Associate (University of Manitoba)
Linda Chow, Technical Staff (University of Manitoba)
Emmelia Wiley, Technical Staff (University of Manitoba)

ABSTRACT

This research project will focus on physical and chemical processes in sea ice that affect the vertical transport of mass and energy. Despite sophisticated model predictions of the global climate including the Polar Regions major gaps in basic sea ice knowledge exist. While the conceptual framework for greenhouse gas transport is increasingly supported by observations there are still major unknowns. In fact, the transport of any material (gases, liquids, and precipitates) through sea ice is poorly understood. Even the release of brine from sea ice to the underlying ocean is poorly studied, especially with respect to its seasonal evolution and kinetics of formation. The objective of our project is to investigate and quantify the importance of fundamental biogeochemical processes using state-of-the-art assessment techniques in a comprehensive three-pronged approach linking small-scale ice tank (cold rooms), meso-scale ice tank (Sea-ice Environmental Research Facility, SERF, at the University of Manitoba) and *in situ* sea ice studies. Specifically, we have two major goals, which relate to climate change impacts in the Arctic: (a) To investigate transport processes, and biogeochemical modification of solutes and precipitates associated with thin ice in polynyas and leads, and (b) to investigate the impact of increasing snow cover on biological, chemical, and transport processes within sea ice.

KEY MESSAGES

Sea Ice Biogeochemical Cycling

- A new method that uses dissolved inorganic carbon to determine ikaite concentration in sea ice is being developed.
- We have improved the understanding of gas transport/accumulation in sea ice.
- We are working on sea ice as an interface for methane storage and transformation.
- Ikaite precipitation within sea ice is active and variable with phases of precipitation and dissolution, depending on ice temperature.
- Up to 57% of ikaite precipitated in sea ice is expelled to underlying seawater, likely via brine rejection.
- Rejection of ikaite crystals from the ice to the underlying seawater keeps the seawater pCO_2 undersaturated compared to the atmosphere during ice growth.
- Multi year sea ice (MYI) seems to be void of CO_2, eliminating air-sea CO_2 flux.

Sea Ice Physical Properties and Processes

- Replacement of old sea ice by first year sea ice in the Beaufort Sea is quantified.
- Delayed freeze up, not breakup timing, is responsible for lengthened summer open water duration.
- Increased first year sea ice may be affecting the formation of the Cape Bathurst flaw lead polynya.
- Winter and summer atmospheric patterns associated with year-to-year variations in September sea ice extent (SIE) correlate with positive winter Arctic Oscillation (AO) and negative summer AO, respectively.
- The interannual variations of winter and summer AO indices after 2007 are weakly connected with year-to-year variations in September SIE.
- Since 2007, surface air temperature over the Beaufort, Chukchi and East Siberian seas is related to interannual variations of September SIE.

Ice Algae and Under-ice Algal Blooms

- Development/use of a non-intrusive approach to determine the changes of photosynthetic parameters of ice algae, sinking algae and phytoplankton over spring is ongoing.

- Photosynthesis (CO_2 uptake by algae) changes in spring depending on light intensity.
- Ice algae, sinking algae, and phytoplankton have different CO_2 uptake levels over spring.

Pesticide Dynamics at the Ocean-Sea ice-Atmosphere Interface

- We present the first direct evidence that melt ponds concentrate, and later release, current use pesticides (CUPs) to the Arctic Ocean at the ocean-sea ice-atmosphere interface in Resolute Passage.
- While melting and falling snow were initially responsible for relatively high concentrations in melt ponds, the ultimate long-term control was gas exchange.
- Gas exchange modeled from air concentrations provides a reasonable regional estimate of flux.

OBJECTIVES

Sea Ice Biogeochemical Cycling

- Identify ikaite crystals in sea ice and develop a new method of quantifying their concentration.
- Develop a new methodology to study air porosity in sea ice, identifying and quantifying sea ice air volume fraction.
- Understand the physical and the biogeochemical processes controlling gas dynamics within sea ice.
- Monitor CH_4 content in sea ice and in the underlying seawater to evaluate if sea ice is a source or sink for atmospheric CH_4.
- Examine the main processes responsible for major changes in the inorganic carbon system of sea ice and the underlying seawater and quantify fluxes of inorganic carbon between the atmosphere, sea ice and the water column from sea ice formation to melt.
- Determine the role of snow on the inorganic carbon dynamic within sea ice and the air-ice CO_2 fluxes.
- Complete the first study of inorganic carbon dynamics in a MYI environment.

Sea Ice Physical Properties and Processes

- Provide an updated climatological analysis of the partial concentrations of multiyear sea ice, first year sea ice and new and young sea ice in the Beaufort Sea annually from 1983-2014, with emphasis on changes observed since 2004.
- Understand importance of the winter and summer AO on the Arctic sea ice.

Ice Algae and Under-ice Algal Blooms

Assess the carbon uptake by the different algal communities present over spring in sea ice and the underlying seawater by:

- Characterizing changes of photosynthetic parameters of ice algae during spring and links to the environmental conditions.
- Comparing the photoprotective properties of ice algae over the spring bloom and between low and high snow covers.
- Comparing the evolution of photosynthetic parameters between ice algae, sinking algae and phytoplankton during spring, and especially during the melting period.

Pesticide Dynamics at the Ocean-Sea ice-Atmosphere Interface

- Present measured CUP and legacy organochlorine pesticide (OCP) concentrations in melt ponds on landfast first-year ice (FYI) in Resolute Passage as a function of gas exchange duration.

- Determine the relative importance of gas exchange, initial snowmelt, precipitation and dilution with melting ice, for concentrations of contaminants in ponds.
- Describe the influence of a June ice cover on fluxes, concentrations, and relative loadings of dacthal to the Polar Mixed Layer of the ocean, emphasizing the implications for biological exposures.

INTRODUCTION

Sea Ice Biogeochemical Cycling

Ikaite ($CaCO_3 \cdot 6H_2O$) precipitates out of sea ice at approximately -2.2ºC (Assur, 1958). Ikaite has been observed in both Antarctic and Arctic sea ice (Dieckmann et al., 2008) and may play a significant role in the sea ice carbon pump (Rysgaard et al., 2011), but the spatial and temporal dynamics of ikaite in sea ice are poorly understood. To increase the understanding of its role in the sea ice carbon pump, an effective and efficient method of quantifying ikaite must be developed. The current time consuming method consists of image analysis of small quantities of ice (e.g. Rysgaard et al., 2013). A new, more efficient method being developed uses dissolved inorganic carbon (DIC) analysis of ice cores.

Each year, 7 Pg of anthropogenic carbon are released to the atmosphere, 29% of which is estimated to be taken up by the Oceans through physical, chemical and biological processes (Sabine et al., 2004). The Arctic Ocean plays a key role in these processes, taking up 5-14% of the global ocean CO_2 uptake (Bates and Mathis, 2009), primarily through primary production and surface cooling (MacGilchrist et al., 2014). However, polar ocean CO_2 uptake estimates ignore the potential role of ice-covered areas on gas exchange between the ocean and atmosphere. Sea ice-covered areas participate in the variable sequestration of atmospheric CO_2 by the ocean (e.g. Geilfus et al., 2012). Studies are required to elucidate the processes responsible as well as their temporal and spatial magnitudes.

The presence of a gas phase in sea ice creates the potential for gas exchange with the atmosphere; the formation of air inclusions and transport of gases within sea ice is still poorly understood (Crabeck et al., 2014). The lack of detailed description of gas filled porosity is in large part due to methodological challenges. Modeling efforts using mushy layer theory also currently neglect the presence of gaseous inclusions in sea ice. Current understanding of the morphology and connectivity of air inclusions in sea ice is inadequate but important for the most accurate interpretation of sea ice data and for use in regional and global climate models. To better understand sea ice gas dynamics, Crabeck et al. (2015) proposed methodological improvements to the measurement of air inclusions within sea ice. The limitations of thin section microscopy motivated the use of non-destructive computed tomography (CT) X-ray imaging. A method to produce separate 3-D images of air inclusions in sea ice cores using CT X-rays, applied mathematics and gas chromatography is currently being developed.

Current atmospheric levels of CH_4 are unprecedented in at least the last 650 kyr, and the Arctic Ocean was shown to be a net source of atmospheric methane by Parmentier et al. (2013), whose recent airborne measurements in the central Arctic basin have shown substantial methane emissions around 2 mg m^{-2} d^{-1} in areas of open leads and fractional ice cover. Damm et al. (2007) and Kort et al. (2012) reported methane supersaturation in Arctic surface waters and point to marine sediment as the main source. Quantification of CH_4 concentrations in bulk sea ice is a primary focus to quantify the effect of sea ice cover on methane emissions to the atmosphere in Arctic waters.

Sea Ice Physical Properties and Processes

Climate change in the Northern Hemisphere has caused the Arctic to warm (Walsh, 2014, Screen and

Simmonds, 2010). In particular, warmer conditions in the recent decade are associated with the rapid decrease of Arctic summer sea ice extent. Arctic surface warming is linked to heat exchange between the atmosphere and ocean. We study how atmospheric circulation influences warmer temperatures over the Arctic and decreased Arctic sea ice extent. The Arctic Oscillation (AO) is an important factor in the atmospheric conditions of the Northern Hemisphere. We examine whether wintertime and/or summertime AOs play an important role in year-to-year variations of September Arctic sea ice extent.

The Beaufort Gyre has played a key role in forming multiyear ice that is later exported to other Arctic regions. This makes increased multiyear ice melt within the Beaufort Sea significant; between 2005 and 2008 it accounted for approximately one-third of the pan-Arctic reduction in multiyear ice (Kwok and Cunningham, 2010). If multiyear ice is no longer able to survive the southern pass of the Beaufort Gyre through the Beaufort Sea, the clockwise journey of multiyear ice may cease and have consequences downstream of the Beaufort. Specifically, younger ice will be recirculated within the Beaufort Gyre and transported into the Transpolar Drift Stream, which has implications for the type and thickness of sea ice exported through Fram Strait or transported back into the Beaufort Sea. Subregional analysis focusing on the Beaufort Sea is therefore vital.

Ice Algae and Under-ice Algal Blooms

In the ice-covered central Arctic, up to 57% of primary production is associated with ice algae (Arrigo et al., 2010). Light determines the beginning of the algal growth, and nutrient concentrations influence bloom duration. This work indicates sea ice microalgae possess high photosynthetic plasticity to acclimatize and protect themselves. However, Petrou et al. (2011) showed that plasticity and photoacclimation of Antarctic diatoms depend of their niche habitats. Ice algae in the bottom sea ice and sinking could possess different photoacclimation capacities. Under-ice blooms have been increasingly observed at the end of spring recently, when light penetrating through the ice is sufficient to support algal growth. These under-ice blooms can be composed of phytoplanktonic centric diatoms *vs* sympagic pennate diatoms as observed by Galindo et al. (2014). Antarctic studies showed that the sympagic pennate diatoms have higher photoprotection capacities, but no study has compared the plasticity of both communities (ice algae vs phytoplankton) at the same time. Understanding photoprotection mechanisms and the evolution of photosynthetic properties of algal communities is imperative in a changing sea ice environment. These data will improve climate change models with the addition of algal physiological adaptations to light, better estimating primary production (CO_2 uptake) over spring in the Arctic.

Pesticide Dynamics at the Ocean-Sea ice-Atmosphere Interface

Sea ice cover has also traditionally been perceived as a barrier to air-sea organic contaminant exchange, but virtually no studies have examined the process at the ocean-sea ice-atmosphere interface, especially during the transition from winter to summer (Pućko et al., 2015). Relatively high concentrations of selected CUPs, found between 1999 and 2001 in small inland lakes and a melt pond on Ward Hunt Island in the Canadian high Arctic were attributed to snow melt (Muir et al., 2004). We hypothesize that melt ponds pump organic contaminants into the ocean *via* gas phase deposition in the spring and summer, followed by drainage into the ocean during melt season (Pućko et al., 2015). Based on melt-pond concentrations of organic contaminants estimated from measured air concentrations and gas exchange modeling, this process could theoretically result in release of pond water carrying 2-10 times higher concentration of contaminants than is contained in Arctic surface seawater.

ACTIVITIES

Sea Ice Biogeochemical Cycling

The image analysis and DIC analysis methods of ikaite quantification were tested at the Sea-Ice Environmental Research Facility (SERF) at the University of Manitoba in early February 2015. This was done to simplify the sampling procedure as much as possible before field-testing at Station Nord, Greenland in April 2015. At Station Nord, a total of nine sea ice cores were extracted.

During the SERF experiment in January 2013, ice cores were collected daily to measure bulk ice gas composition (O_2, N_2, Ar), temperature, salinity, density and for CT X-Ray imaging and analysis. Crabeck developed a CT X-ray method to quantify air volume fraction and submitted a paper (Crabeck et al., 2015).

To document the methane dynamics in sea ice-covered waters, seawater, brine, ice cores and sediment cores were collected weekly between May and July 2014 in Young Sound near Daneborg, Greenland. [CH_4] and the CH_4 stable isotope ($\delta^{13}C$-CH_4 and dD-CH_4) will be measured in bulk sea ice, in brine, and in the water column with a specific focus at the ice-water interface and at the sediment-water interface. Samples for isotopic composition still need to be analysed and a paper is in preparation.

Geilfus recently submitted a manuscript detailing results from SERF regarding the export of ikaite from new and young sea ice to Cryosphere Discussions. New data currently undergoing analysis were generated over three weeks at Station North, Greenland. Samples from Station North (2015) still need to be processed and SERF experiments will be undertaken in January and February 2016 at the University of Manitoba.

Ice Algae and Under-ice Algal Blooms

Sampling was conducted from an ice station located in Baffin Bay offshore from the community of Qiqiktarjuak, Nunavut during phase 1 of the GreenEdge project. From 26 April to 10 June 2015, seawater, sea ice and fresh sediment traps were collected. For each sample, the maximum photochemical efficiency of PSII and induction curves were measured in triplicate using a pulse-amplitude modulated (PAM) fluorometer (Water-PAM, Heinz Walz). Chlorophyll *a* (Chl *a*), pigment composition (HPLC), particulate absorption, particulate organic carbon and nitrogen (POC/PON), nutrients, pico- and nano-phytoplankton were also sampled, as were temperature and salinity in sea ice and the water column, along with light beneath the ice. Incubation experiments were run to assess the change of photo-adaptation of algae in function of light treatments.

Pesticide Dynamics at the Ocean-Sea ice-Atmosphere Interface

Currently, lab analysis of meltpond, seawater, and air samples from Resolute is being undertaken, which will be followed by data analysis, and preparation of a manuscript for Environmental Science & Technology. In addition to a recently submitted manuscript, (Pućko M et al.: Current Use Pesticide (CUP) and legacy Organochlorine Pesticide (OCP) dynamics at the Ocean-Sea ice-Atmosphere (OSA) interface in Resolute Passage, Canadian Arctic, during winter-summer transition; ES&T), Pućko has been on maternity leave (5 June 2015 - 31 March 2016).

RESULTS

Sea Ice Biogeochemical Cycling

Based on ikaite crystals that were observed under the microscope, crystals ranged from 5 to approximately 50 µm in length and had a distinct rhombic structure. In first-year sea ice, ikaite concentration varied from

0 to 47.7 µmol kg^{-1} when using the image analysis technique of quantification. Ikaite concentrations in multi-year ice determined using image analysis ranged from 0 to 2.4 µmol kg^{-1}. The ikaite concentration uncertainty ranges from 0 to 76.689 µmol kg^{-1} in first-year ice and from 0 to 3.398 µmol kg^{-1} in multi-year ice.

Ikaite concentrations determined using DIC analysis method were generally lower than those calculated using the image analysis method in first-year ice. Concentrations ranged from 1.791 to 11.978 µmol kg^{-1} in first-year ice, which is from 0.033 to 19.257 µmol kg^{-1} different than concentrations obtained using the image analysis method. In multi-year ice, ikaite concentrations determined using the DIC method were generally higher than those calculated using the image analysis method. Concentrations in multi-year ice ranged from 1.120 to 6.663 µmol kg^{-1}, which is from 0.861 to 6.664 µmol kg^{-1} different than concentrations obtained using the image analysis method.

CT X-ray imaging is a reliable non-destructive method to identify and quantify the air volume fraction in sea ice. CT-imaged sea ice air-volume fractions were always lower than 2% in columnar sea ice but systematically exceeded 5% in granular sea ice near the sea ice-atmosphere interface. Air volume fraction increased as ice grew thicker in columnar and granular sea ice. Methane concentrations in seawater underlying sea ice and in the sea ice were supersaturated compared to the atmosphere and methane accumulation under and within sea ice was observed. Incubation experiments showed potential CH_4 formation in sea ice in anoxic pockets.

At SERF (January 2013) TA and TCO_2 in seawater were sampled. During sea ice growth, TA increased (Figure 1a) while TCO_2 increased (Figure 1b). Once the ice started to melt, TA decreased and TCO_2 decreased. To discard the effect of salinity changes, we normalized TA and TCO_2 to a salinity of 33 (noted as *n*TA and $nTCO_2$). During ice growth, *n*TA and $nTCO_2$ increased slightly (Figure 1c). However, once the ice started the melt, *n*TA and $nTCO_2$ increased.

The *in situ* pCO_2 of the underlying seawater decreased from 377 to 360 ppm as the seawater temperature in the pool decreased to the freezing point. The pCO_2 then oscillated from 360 to 365 ppm during sea ice growth. As the pool was heated from the bottom, the pCO_2 returned to a similar concentration as at the beginning of the experiment. Within sea ice, TA and TCO_2 averaged daily for the volume decreased from the beginning to the end of the experiment.

Sea Ice Physical Properties and Processes

We examine the influence of winter and summer AO on variations in the September Arctic SIE, providing evidence that both winter and summer AOs are correlated with year-to-year differences of the September Arctic sea ice extent (SIE). The atmospheric patterns are characterized by winter cyclonic circulation anomalies over East Greenland and summer anticyclonic circulation anomalies that are similar to the AO during both winter and summer. The winter and summer AO indices proved to be good predictors of Arctic SIE from 1979-2007. However, the predicted SIE using the winter and summer AO indices was poor after 2007.

Addition of 2005-2014 to the longer 1983-2004 time series increased prevalence of sea ice concentration trends in the Beaufort Sea and revealed marked spatial variability of monthly sea ice concentration trends by stage-of-development (Figure 2). Between 1983 and 2014, total and old sea ice losses in summer and fall months yield substantial decreasing old ice concentration trends and increasing first year concentration trends between Jan and Jun (Figure 2). Positive new-plus-young sea ice concentration trends occur in the 1983-2014 time series in Oct and/or Nov in each of the five Beaufort subregions, indicating that freeze up and related sea ice thickening occurs later and has proceeded more slowly over the long term, or that there is more open water at the end of summer which then experiences sea ice formation in autumn. Between 1983-2014, negative total sea ice trends occurred in more summer months of the year in more of the subregions of the Beaufort Sea,

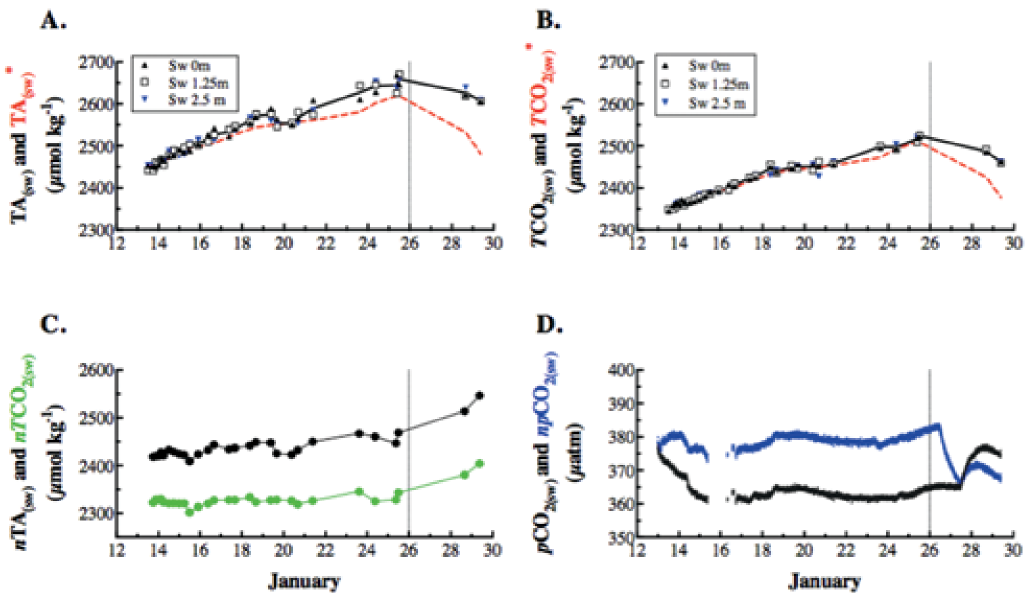

Figure 1. Evolution of (A) TA and TA(sw)(µmol kg^{-1}), (B) TCO_2 and TCO_2(sw)* (µmol kg^{-1}), (C) nTA and $nTCO_2$ (µmol kg^{-1}) and (D) the seawater pCO_2 (µatm) measured in situ (black) and corrected to a constant temperature of -1°C (blue). In panels (A) and (B) the black line is the average over three depths while the dotted red line is the expected concentrations according to the observed salinity. The vertical black dotted line on 26 January marks when the heat was turned on.*

which temporally evolve into increasing trends in new-plus-young and first year ice concentrations in autumn. As the Beaufort Sea progresses annually into winter, what follows are increasing trends in first year sea ice combined with the nearly equal and opposite decreasing trends in old ice concentrations throughout the winter and spring months in especially the south and west subregions of the Beaufort Sea (Alaska, Mackenzie and Canada basin) (Figure 2).

Ice Algae and Under-ice Algal Blooms

From May to mid-June, Chl *a* concentrations increased in the bottom sea ice. Over this period, the Chl *a* concentration was lower than 1µg/L in the underlying water column. The photosynthetic yield II (PSII) was around 0.3-0.5 for the bottom ice algae, while it was slightly higher in the upper water column (0.4-0.7) and in fresh sediment traps (0.4-0.6) over spring. Rapid light curve measurements allowed the assessment of the photosynthetic efficiency (α) and the maximal electron transport rate (rETRmax). Different snow cover had no impact on these values. The values of α in bottom ice algae were in the same range than those in the sinking algae but lower than those in phytoplankton over spring. The values of rETRmax in ice algae were lower than those in phytoplankton and in sinking algae. The values of rETRmax were relatively constant until the beginning of June when they started to increase.

Pesticide Dynamics at the Ocean-Sea ice-Atmosphere Interface

Four major stages occur during melt-pond evolution are detailed by Eicken et al., (2002). Contaminant sources vary among stages. In stage I (10th - 14th June) (Landy et al., 2014), organic contaminants were delivered to melt ponds mainly from melting snow and sea ice, but also *via* gas phase exchange processes and wet deposition from the atmosphere. At Stage II, (14th to 21st June), gas deposition becomes an important source. Toward the beginning of stage III, there may be upward percolation of seawater into some melt ponds as observed with α-HCH. Finally, during stage

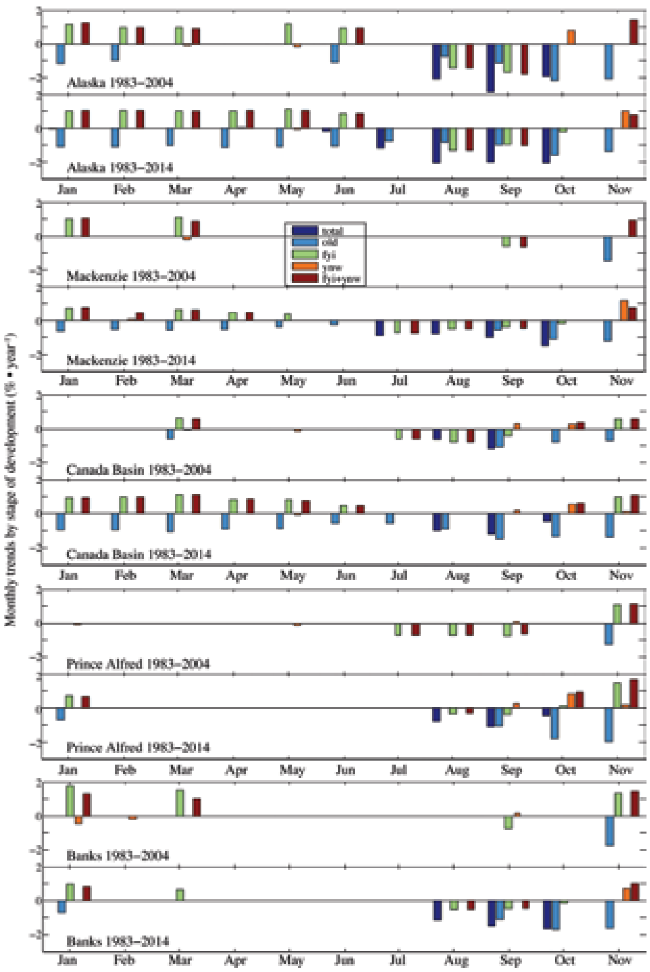

Figure 2. Trends (%yr-1) in monthly mean sea ice concentration by stage of development in the CIS ice regime sub-regions that make up the Beaufort region from 1983-2004 and from 1983-2014. Trend data only presented where $p < 0.10$.

III (29th June – 4th July), accumulated contaminants are released into the ocean.

OCPs and CUPs in this study can be divided into those: 1. Present in melt ponds and snow, and 2. Absent from melt ponds but detected in snow. The former category comprises mainly CUPs and one OCP (α-HCH). All the contaminants in that group reached higher average concentrations in melt ponds than in snow. The latter group includes mainly OCPs and one CUP. All compounds within that group were initially detectable in snow, decreased to below-detection-limit concentrations before the snow melted and were never detected in melt ponds.

DISCUSSION

Sea Ice Biogeochemical Cycling

The DIC method yielded higher ikaite concentrations than the image analysis method in all sections in multi-year ice. This is because very few ikaite crystals were observed in multi-year ice, so the image analysis results returned a concentration of 0 µmol kg^{-1} in 13 of 21 sections, and the DIC method returned non-zero results in all cases in multi-year ice. In first-year ice, the image analysis method yielded higher concentrations than the DIC method in 17 of 44 sections. When the DIC method returned higher ikaite concentrations than image analysis, the difference between the two methods was less than 6 µmol kg^{-1}; when the opposite was true the difference between the two methods ranged from 0.5 to 19.3 µmol kg^{-1}. One standard deviation from the mean was used as an error, and in all cases, ikaite concentrations derived using the image analysis and DIC analysis techniques overlapped within error.

Higher ikaite concentrations are expected during the winter when the ice is colder than in the spring and fall. Ice temperatures at Station Nord were warmer than those in other studies that quantified ikaite, and the ikaite concentrations determined at Station Nord were also lower than those in the other experiments. In general, ikaite concentration also decreases with increasing depth in the sea ice, which corresponds with the temperature gradient.

Salinity also affects ikaite concentration in sea ice. Salinity in each ice core extracted during the field campaign in Station Nord form a typical C profile. A higher ikaite concentration is expected when the sea ice has a higher salinity (Rysgaard et al., 2014). The salinity of the seawater at Station Nord was approximately 20, which is much lower than the typical salinity of 27 in seawater, likely due to freshwater input from a nearby ice cap. This accounts for the low salinity in the sea ice as well as the lower than expected ikaite concentrations.

Due to the warm temperatures, low salinity, and low ikaite concentrations at Station Nord, it is difficult to tell whether temperature or salinity has a greater effect on ikaite concentration. Ikaite concentrations decrease with increasing ice depth, but there is sometimes a slight increase in the lowest 10 cm. This seems to indicate that the effect of temperature is greater than the effect of salinity, but that bulk salinity is also a significant factor. However, to be able to better determine whether ikaite concentration is more dependent on temperature or salinity, it is important to quantify ikaite in sea ice with colder temperatures and higher salinity.

The main processes affecting the carbonate system are described by changes in TA and TCO_2 (Zeebe and Wolf-Gladrow, 2001). The carbonate system in sea ice is affected by the precipitation of ikaite and a release of $CO_{2(g)}$ while the underlying seawater is mainly affected by the dissolution ikaite (Figure 3). Since TA and TCO_2 are conservative with salinity, we can calculate the expected TA and TCO_2 (noted as $TA_{(ice)}^*$ and $TCO_{2(ice)}^*$ in the ice cover and $TA_{(sw)}^*$, $TCO_{2(sw)}^*$ for the water column (Figure 1) based on initial seawater conditions (TA, TCO_2 and S) and the sample salinity (sea ice or seawater) measured during the experiment. We assume that half of the difference between TA(sample)* and TA(sample) is a result of ikaite precipitation when the difference is positive. A negative difference (i.e. TA(sample)* < TA(sample)), implies that a lack of TA is observed in the sample compared to what is expected based on the observed salinity changes, suggesting that ikaite crystals were either dissolved or exported out of the sample.

In sea ice, higher TA^* and TCO_2^* compared to TA and TCO_2 suggested ikaite precipitation. Ikaite precipitation appeared to be highly variable (167 µmol kg^{-1} to 1 µmol kg^{-1}). In the underlying seawater, lower $TA_{(sw)}^*$ and $TCO_{2(sw)}^*$ compared to TA and TCO_2 (Figure 1) confirm the dissolution of ikaite. Export of ikaite crystals from the ice cover to the underlying seawater is likely associated with brine rejection during sea ice growth.

Sea Ice Physical Properties and Processes

Previous studies have only focused on the effect of (i) the preceding winter (e.g., Stroeve et al., 2011) or (ii) the concurrent summer (e.g. Ogi and Yamazaki 2010).

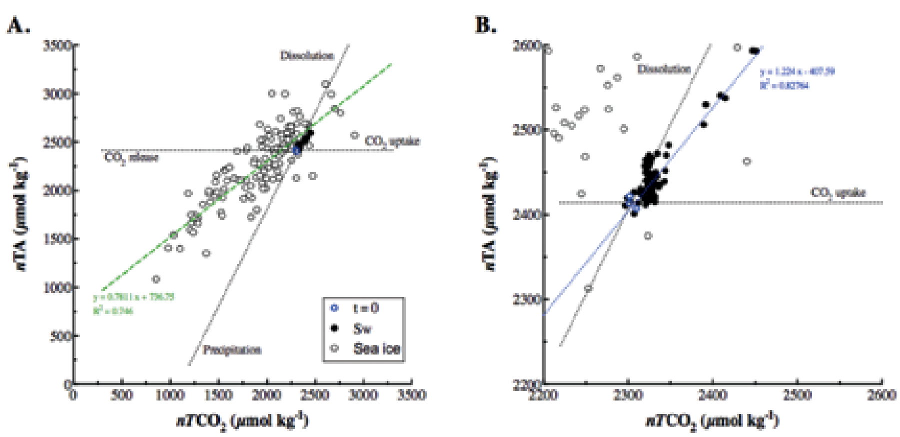

*Figure 3. (**A**) Relationship between $nTCO_2$ and nTA (µmol kg^{-1}) in bulk sea ice (white hexagons) and seawater (black dots), (**B**) Zoom on seawater data. The different dotted lines represent the theoretical evolution of nTA and $nTCO_2$ ratio following the precipitation/dissolution of calcium carbonate and release/uptake of $CO_{2(g)}$.*

We considered the effect of the preceding winter AO and the concurrent summer AO on the September SIE simultaneously. Our study is the first to show that year-to-year variation of the September SIE can be predictable up to 2007 if both winter and summer AO indices are considered.

Why are the winter and summer AO weaker connected to the September SIE after 2007? Previous studies showed that thin sea ice, a ~40% reduced ice volume over 2007-2011, and the presence of ocean heat in the near surface created the 2012 record low Arctic sea ice extent (Zhang et al., 2013). The recent Arctic warming signal is linked to open water areas while the recent sea ice reduction during summer and early fall allows a strong transfer of heat from the ocean to the atmosphere in the subsequent late fall to winter (Screen and Simmonds, 2010). Walsh (2014) also showed that warming after 2007 is strongest over the Arctic Ocean during autumn and winter seasons. 2007 represented a regime shift in the Arctic marine system affecting many aspects of not only the sea ice dynamic and thermodynamic processes but also the atmospheric boundary layer (e.g. Raddatz et al., 2012), and many biogeochemical processes in the Southern Beaufort Sea (e.g. Barber et al., 2012). It is interesting to note that extensive field data shows a clear demarcation in 2007 as does this correlation analysis with the AO and sea ice processes.

Ice Algae and Under-ice Algal Blooms

Chl *a* concentrations in the bottom of sea ice during the GreenEdge project are within the range of those reported in previous studies across the Arctic (e.g. Arrigo et al., 2010). Differentiation between low and high snow cover sites seems extremely difficult due to the constant high wind velocity at the study site. The values of α in bottom ice algae were lower than those in phytoplankton, as previously observed in Franklin Bay (Ban et al., 2006) but in the same range than those in sinking algae, suggesting the sinking algae underneath the ice were mostly composed of pennate diatoms. The increase of rETRmax at the beginning of June for ice algae and phytoplankton could be associated decreased snow thickness favoring the transmission of light through the sea ice, suggesting that ice algae and phytoplankton could rapidly be photo-acclimated to higher light intensity. These observations indicate that numerous changes happen during the snow melt period (the first change of photosynthetic parameters observed).

Pesticide Dynamics at the Ocean-Sea ice-Atmosphere Interface

We performed a Principal Component Analysis (PCA) with HLC (Henry's Law Constant), log*Kow* (octanol-water partition coefficient), C_S (measured average snow concentration), C_A (measured average air concentration), $C_{MP/Mes}$ (measured average melt-pond concentration), $C_{MP/Eq}$ (calculated melt-pond equilibrium partitioning concentration) and $C_{MP\ Mes/Eq}$ (a ratio of $C_{MP/Mes}$ to $C_{MP/Eq}$) as factors (Figure 4). The first two PCs explained 48 and 21% of variability in the dataset (a total of 69%). Water solubility (represented by HLC), organic carbon-partitioning potential (represented by log*Kow*), and C_A trended with the first PC, positioning two compounds with the highest measured concentrations in melt ponds (α-HCH and dacthal) separately in the graph (red

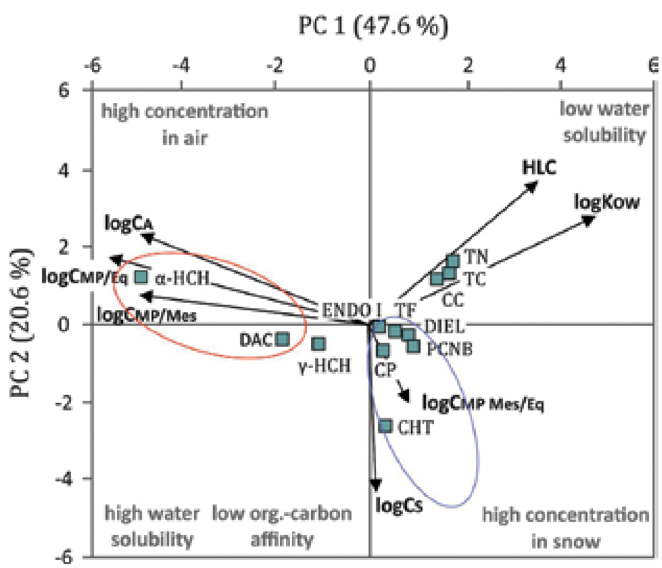

Figure 4. Principal Component Analysis (PCA; correlation matrix) contaminant scores along with relative loadings of factors (log-transformed prior analysis).

group in Figure 4). C_A was also positively correlated with $C_{MP/Mes}$ and $C_{MP/Eq}$, implying that hydrophilic contaminants that partition strongly to water (low HLC and log*Kow*) and have high concentrations in air are at the highest risk of reaching high dissolved concentrations in melt ponds due to gas deposition over the summer. C_S trended with the second PC, was negatively correlated with HLC and log*Kow*, and positively correlated with $C_{MP\ Mes/Eq}$. Relatively water-soluble larger organic contaminants that are easily scavenged from the atmosphere by snow (Lei and Wania, 2004), may load to ponds faster than predicted by gas phase exchange processes due to high initial loadings from melting and falling snow. The majority of CUPs were grouped along with C_S (blue group in Figure 4); however, only those that remain at relatively high concentrations in snowpack until the melt-pond onset end up at relatively high levels in meltwater (chlorpyrifos, pentachloronitrobenzene, trifluralin). Others (chlorothalonil, endosulfan I, dieldrin) were either outgassed to the atmosphere or flushed out of the snow during the first spring flushing before the melt ponds started forming in the area (Halsall, 2004).

CONCLUSION

Sea Ice Biogeochemical Cycling

Based on results from the Station Nord field campaign, the DIC method seems to be an effective method of quantifying ikaite. However, the warm temperatures and low salinities result in lower than expected ikaite concentrations.

As a result of the presence of large bubbles and higher air volume fraction measurements in sea ice we introduce new perspectives on processes regulating gas exchange at the ice-atmosphere interface, and note that the air volume fraction should be an important inclusion in parameterizations of sea ice permeability. CT X-ray imaging may allow for visualizations of transport pathways. This information is vital to the improvement of models involving transport of biochemical compounds and gas transfer between the ocean and the atmosphere in polar oceans.

Based on TA and TCO_2 measurements at SERF, our estimation of 1 to 167 µmol kg^{-1} ikaite precipitated in sea ice matched the previous estimation from Rysgaard et al., (2014). We estimate only ~43% of the ikaite precipitated within sea ice remained in the ice. During sea ice melt, ikaite is likely flushed out the ice cover. Ikaite export and its dissolution in the water column had a strong impact on the $pCO_{2(sw)}$. During the experiment, $pCO_{2(sw)}$ was undersaturated compared to the atmosphere, in spite of brine and TCO_2 rejection and the increase of the seawater salinity, $TA_{(sw)}$ and $TCO_{2(sw)}$.

Sea Ice Physical Properties and Processes

We have provided evidence that both winter and summer AO are correlated with year-to-year differences of September Arctic SIE. The winter and summer AO indices proved to be a good predictor of September SIE from 1979-2007. However, the predicted September SIE using the winter and summer AO indices was poor after 2007. Results from our study point out that autumn surface temperature over the Beaufort, Chukchi and East Siberia seas closely relates to the September SIE since 2007.

Between 1983 and 2014, summer reductions in total sea ice concentration between -10% to -15%·decade^{-1} via reductions in old (-5% to -10%·decade^{-1}) and first year sea ice (-5%·decade^{-1}) concentrations over increasingly large areas and in more months per year. Total sea ice losses were observed to occur earlier in summer in the southerly and westerly parts of the study region in the 1983-2014 time series compared to the time series ending in 2004. Those summer changes are followed by thermodynamic freeze up that became increasingly delayed and occurred over an increasingly large area through 1983-2014. Retardation of thermodynamic freeze up and dynamic forcing on the sea ice has increased the summer open water duration in much of the study region.

Ice Algae and Under-ice Algal Blooms

Our study improves our knowledge of the physiological adaptation to light of ice algae and the underlying phytoplankton, two communities in perpetual co-existence. This time series over spring represents an important dataset in a field rarely studied in the Arctic.

Pesticide Dynamics at the Ocean-Sea ice-Atmosphere Interface

CUPs are at a relatively high risk of reaching high concentrations in melt ponds over the summer (Pućko et al., 2015), a process ultimately determined by gas exchange. Most CUPs were designed to have relatively low HLCs to reduce their persistence in air and therefore not undergo long-range transport (Hermanson et al., 2005). However, they are found routinely in Arctic air and water (e.g. Zhang et al., 2013). As a result, CUPs are predisposed for loading into melt ponds due to their relatively high water solubility and presence in the Arctic atmosphere. Whether particular CUPs will reach concentrations high enough to pose danger for biological exposure following melt-pond drainage can be determined by the Melt-pond Enrichment Factor (a ratio of concentration in melt pond to concentration in the interface seawater). Since CUP presence in the Arctic air is highly dynamic, possibly periodic, and dependent on various factors including season, lapse rate, and horizontal and vertical motion of the atmosphere (Hermanson et al., 2005), loading of particular CUPs to melt ponds may differ temporally and spatially over the Arctic Ocean. However, C_A and the modelled gas flux would present a logical first approach to determine the regional and temporal susceptibility to melt-pond loading.

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Understanding the Effects of Climate Change and Industrial Development on Contaminant Processes and Exposure in the Canadian Arctic Marine Ecosystem: How Can we Prepare?

Project Leader

Gary Stern (University of Manitoba)

Network Investigators

David G. Barber (University of Manitoba)
Jasmine Brewster (University of Manitoba)
Steven Ferguson (University of Manitoba)
Louis Fortier (Université Laval)
Brendan Hickie (Trent University)
Holger Hintelmann (Trent University)
Liisa Jantunen (Environment Canada - Science and Technology Branch)
Zou Zou Kuzyk (University of Manitoba)
Lisa Loseto (Fisheries and Oceans Canada - Freshwater Institute)
Robie W. Macdonald (Fisheries and Oceans Canada - Institute of Ocean Sciences)
Peter Outridge (University of Manitoba)
Jean-Eric Tremblay (Université Laval)
Feiyue Wang (University of Manitoba)

HQP

Lekhnath Ghemire, Doctoral Student (Trent University)
An examination of the impacts of Arctic climate fluctuations on mercury concentrations in Ulukhaktok ringed seals (Phoca hispida) using mercury stable isotopes
Kang Wang, Doctoral Student (University of Manitoba)
Durell Desmond, Masters Student (University of Manitoba)
Jake Ritchie, Masters Student (University of Manitoba)
Wen Xu, Masters Student (University of Manitoba)
Kathleen Munson, Post-Doctoral Fellow (University of Manitoba)
Corinne Pomerleau, Post-Doctoral Fellow (University of Manitoba)
Alexis Burt, Research Associate (Fisheries and Oceans Canada - Freshwater Institute)
Ashley Gaden, Research Associate (University of Manitoba)
Monika Pucko, Research Associate (University of Manitoba)
Debbie Armstrong, Technical Staff (University of Manitoba)

ABSTRACT

Recent studies have shown that climate change is already having significant impacts on many aspects of transport pathways, speciation, cycling and exposure of contaminants within Arctic ecosystems. For example, the extensive loss of sea-ice in the Arctic Ocean and the concurrent shift from greater proportions of perennial to annual types have been shown to promote changes in primary productivity, food web structure, mercury methylation and demethylation rates, and mercury distribution and transport across the ocean–sea ice atmosphere interface (bottom-up processes). Changes in animal social behavior associated with changing sea-ice regimes are now known to affect dietary exposure to contaminants (top-down processes). In addition to the climate effects on contaminant cycling and exposure in the Arctic, the changes currently underway in sea ice cover, and market pressures for new resources, have resulted in a significant increase in planned or prospective natural resource development. In particular, there has been a resurgence of interest from oil and natural gas companies in exploration and development licensing. Additionally, shipping traffic through the Canadian Arctic is predicted to increase with decreasing ice concentrations. The environmental issues surrounding oil spills in ice-covered waters; however, remain a key concern of all stakeholders.

The proposed study will provide valuable scientific information needed to support Arctic governments in their efforts to take remedial and preventive actions relating to contaminants and adverse effects of climate change and industrial development in the Arctic marine environment. It will help answer the question "How can we prepare?"

KEY MESSAGES

Mercury in the High Arctic Ocean and Hudson Bay under a Changing Climate

- *Atmosphere:* Bromine activation during the Arctic springtime, which affects atmospheric mercury (Hg) deposition, takes place in the snow instead of sea ice. The snow bromide is derived primarily from non-sea-salt sources.
- *Sea ice:* A general, mechanistic model is developed to differentiate between the incorporation of particulate Hg into frazil ice and the scavenging of atmospheric Hg in surface crystals.
- *Seawater:* In addition to the highest methylmercury (MeHg) production in Arctic seawater at the depth of oxycline, elevated MeHg concentration is also observed at the depth of the sub-surface chlorophyll maximum.
- *Geographical variation:* The total Hg concentration in seawater is much higher in the Baffin Bay area than the rest of the Canadian Arctic Ocean.

Pan-Arctic concentrations of mercury and stable isotope ratios in zooplankton

- Biomagnification rates of MeHg among zooplankton are highest in the southern Beaufort Sea.
- Seawater Hg concentration is controlling factor towards Hg concentrations in zooplankton.

Examining Arctic climate fluctuations on mercury concentrations in Ulukhaktok ringed seal (Phoca hispida) using stable mercury isotopes

- Mercury (Hg) isotope ratios are potentially useful to examine biological and environmental factors affecting the bioaccumulation of Hg in the Arctic marine environment.

- Measuring the mass-dependent (MDF) and mass-independent fractionation (MIF) of Hg stable isotopes in ringed seals will help us to develop an understanding of factors driving the relationship between fluctuations in Hg concentrations in seal tissues and the extent of ice cover (measured as the number of ice-free days).

Mercury concentrations in a Beaufort coastal marine protected area

- Investigating similarities in diet and habitat use of 16 species of co-occurring fish at Shingle Point, NT, we discovered that species could be grouped into three isotopic and five fatty acid groups.

Pesticide dynamics at the Ocean-Sea ice-Atmosphere (OSA) interface during winter-summer transition

- We present the first direct evidence that melt ponds concentrate and later release current use pesticides (CUPs) to the Arctic Ocean based on data collected in 2012 at the ocean-sea ice-atmosphere interface in Resolute Passage, Canadian Arctic.

Organophosphate ester flame retardants and plasticizers (OPEs) in the Arctic

- Chlorinated organophosphate esters (OPEs; persistent organic pollutants) are slightly decreasing in Arctic air samples, whereas non-chlorinated OPEs are increasing slightly.

Polycyclic Aromatic Hydrocarbons in benthic invertebrates from Baffin Bay

- The enhanced accuracy and detection limits of our new laboratory instrumentation will build upon and improve our hydrocarbons dataset.

Interactions between oil and sea ice

- Experiments with crude oil in a sea ice environment have begun (Jan-Feb 2016) at the Sea-ice Environmental Research Facility at the University of Manitoba.

OBJECTIVES

Mercury in the High Arctic Ocean and Hudson Bay under a Changing Climate

- To understand biogeochemical cycling of Hg, especially Hg methylation, in seawater and the sea ice environment in the Arctic Ocean including Hudson Bay;
- To develop a mass balance model of MeHg in the Arctic Ocean including Hudson Bay;
- To assess the relative contribution of climate change and other processes (e.g., hydroelectric regulations) in MeHg production in Hudson Bay.

Pan-Arctic concentrations of mercury and stable isotope ratios in zooplankton

- To assess the regional differences in zooplankton Hg concentrations;
- To examine the trophic ecology of key zooplankton species;
- To evaluate Hg biomagnification within two predator-prey linkages, *Calanus* spp.-*Themisto* spp. and *Calanus* spp.-*Paraeuchaeta* spp.

Examining Arctic climate fluctuations on mercury concentrations in Ulukhaktok ringed seal (Phoca hispida) using stable mercury isotopes

- To determine whether an increase in the number of ice-free days (and hence an increase in light regime) will enhance the photodemethylation of MeHg in the marine water column which may be shown by declines in total Hg (THg), MeHg and an increase in the mass-independent fractionation of Hg isotopes (expressed as $\Delta^{199}Hg$) in seal tissue;

- To determine whether changes in diet, as exemplified by stable isotope ratios of nitrogen and carbon ($\delta^{15}N$ and $\delta^{13}C$, respectively) and possibly fatty acid signatures, also change with extent of ice cover and how these may affect Hg isotopic signatures.

Mercury concentrations in a Beaufort coastal marine protected area

- To identify where in the coastal environment mercury (Hg) is accumulating using isotopic signatures and Hg concentrations of fish species;
- To use Hg as a trophic marker to see how Hg behaves in this coastal environment;
- To identify where fish in our study region are possibly introducing these Hg concentrations, since many of these species are anadromous.

Pesticide dynamics at the Ocean-Sea ice-Atmosphere (OSA) interface during winter-summer transition

- To determine the roles of gas exchange, initial snow melt, precipitation, ice cover and ice melt with respect to concentrations of contaminants in ponds;
- To quantify current use pesticide (CUP) and legacy organochlorine pesticide (OCP) concentrations in melt ponds as a function of gas exchange duration.

Organophosphate ester flame retardants and plasticizers (OPEs) in the Arctic

- To determine the occurrence and levels of OPEs in Canadian arctic air;
- To analyze archived air samples to determine spatial and temporal trends of OPEs in Canadian archipelago air.

Polycyclic Aromatic Hydrocarbons in benthic invertebrates from Baffin Bay

- To establish baseline levels of petroleum hydrocarbons in Baffin Bay's sediments, water and foodwebs;
- To develop diagnostic approaches and analytical methods that can be used to distinguish oils and other hydrocarbons from local "petrogenic" (i.e. from regional geological sources), foreign petrogenic (i.e. oil produced elsewhere and carried in Arctic ship traffic), and long-range combustion sources, in advance of new oil exploration initiatives and increased shipping traffic.

Interactions between oil and sea ice

- To examine the properties of oil and sea ice as they interact in an artificial mesocosm;
- To determine which components of crude oil have been absorbed into sea water, have been adsorbed just below the sea ice, and which components have percolated up into the sea ice.

INTRODUCTION

Mercury in the High Arctic Ocean and Hudson Bay under a Changing Climate

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 Hg emissions; instead, they are increasingly driven by climate-induced changes in post-depositional processes that control the transport, transformation, and biological uptake of stored Hg 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 Hg flux to the underlying marine ecosystem (Burt et al. 2013; Chaulk et al. 2011; Chaulk 2011). We have also shown a profound production zone of MeHg in sub-surface seawater in Beaufort Sea (Wang et al. 2012), and potential MeHg production in the Arctic multi-year sea ice (Beattie et al. 2014). However, major uncertainties exist with respect to the net transport of atmospheric Hg to the ocean, the mechanism by which sea ice affects the net atmospheric transport of Hg, and the process responsible for MeHg production in seawater and sea ice.

Pan-Arctic concentrations of mercury and stable isotope ratios in zooplankton

Zooplankton are primary consumers in marine food webs, acting as "keystone" species in the transfer of Hg up through the marine food chain. However, little is known about the biomagnification of Hg within zooplankton, although there is clear evidence that it occurs. Given the dominant role that zooplankton play in supporting higher trophic levels in the marine ecosystem, it is important to further our understanding of the Hg uptake and transfer within zooplankton communities and the implications for higher trophic level species within these northern regions.

Examining Arctic climate fluctuations on mercury concentrations in Ulukhaktok ringed seal (Phoca hispida) using stable mercury isotopes

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, recent work by our group has shown that Hg concentrations in ringed seals vary depending on the extent of sea-ice cover in the preceding winter (Gaden et al. 2009). More recent work (Point et al. 2011) showed that Hg stable isotopic signatures in Arctic seabirds were also affected by sea-ice cover, which they attributed to changes in MeHg photodegradation rates in the ecosystem. Building on these studies, we will test the hypothesis that changes in the ice-related light regime will affect the net pool of MeHg at the base of the food web by changing photo-demethylation rates which may be tracked by characteristic mass-independent fractionation of Hg stable isotopes (Hg-SI) in ringed seal tissues.

Mercury concentrations in a Beaufort coastal marine protected area

Shingle Point is an important historical and modern day fishing community for the northern peoples in the Western Canadian Arctic. This coastal spit is part of the Tarium Niryutait Marine Protected Area (TNMPA) and is an intermediate habitat to a diverse population of fishes in the summer months before they return to their respective marine and freshwater habitats. Our study investigating Hg inputs into the coastal region of this protected area will provide critical information needed to support the TNMPA.

Pesticide dynamics at the Ocean-Sea ice-Atmosphere (OSA) interface during winter-summer transition

Although sea ice cover has traditionally been perceived as a barrier to organic contaminant exchange between seawater and air, there have been virtually no studies examining the process at the ocean-sea ice-atmosphere (OSA) interface, especially during the transition from winter to summer (Pućko et al. 2012, 2015). Recently we have hypothesized that melt ponds pump organic contaminants into the ocean via gas phase deposition in the spring and summer, followed by drainage into the ocean during melt season (Pućko et al. 2015). Based on melt-pond concentrations of organic contaminants estimated from measured air concentrations and gas exchange modelling, this process could theoretically result in release of pond water carrying 2-10 times higher concentration of contaminants than is contained in surface seawater into the Arctic Ocean.

Organophosphate ester flame retardants and plasticizers (OPEs) in the Arctic

Organophosphate esters (OPEs) are synthetic chemicals used in many polymer-based consumer and industrial products to reduce their flammability in order to comply with flammability standards (van der Veen et al. 2012). OPEs have been in use for decades, however, their use increased significantly since the listing of several brominated flame retardants as persistent organic pollutants (POPs) under the Stockholm Convention. Several OPEs have a persistence similar to the brominated flame retardants they are replacing (Zhang et al. 2016). Moreover, increasing evidence indicates that OPEs have endocrine disruptive properties (Oliveri et al. 2015), reproductive or developmental toxicity (WHO 1998) and, in the case of chlorinated OPEs, carcinogenicity (van der Veen et al. 2012).

Polycyclic Aromatic Hydrocarbons in benthic invertebrates from Baffin Bay

The largest prospective under-sea oil reserves in Canada occur beneath Baffin Bay (including the North Water Polynya, Davis Strait, Lancaster Sound, and Jones Sound) which possibly contains as much as 10 billion barrels of oil. Development of this resource carries risks of spills at all stages of exploration and production. Other possible sources of crude oil contamination in Arctic marine ecosystems include natural oil seeps and oil spills from ships transporting oil sourced from other regions. Understanding the sources and fate of oil in ice and in the surrounding seawaters and biota are essential for the conduct of environmental risk assessments, the development of oil spill countermeasures, apportioning responsibility, and the monitoring of habitat recovery in the event of a spill.

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, sensors for detecting oil in ice and snow require much further research as the difficulties in detecting oil in ice are vast. For example, weathering of oil spills can greatly alter the chemical properties of the oil. Major short term weathering processes include evaporation, dispersion, and emulsification which governs the overall physical behaviour of the surface slick (e.g. viscosity and volume density) and the mass balance of the oil spill. At SERF we will analyze the chemical properties of oil (e.g. dielectric constant, temperature, polarity) in a sea ice environment to bridge the gap in understanding of oil chemistry and physics which influence remote sensing detection.

ACTIVITIES

Mercury in the High Arctic Ocean and Hudson Bay under a Changing Climate

- March – June 2015: Further analysis and interpretation of data obtained from last year at the Sea-ice Environmental Research Facility (SERF) and in Cambridge Bay on bromine and Hg chemistry in snow and sea ice.
- April – May 2015: Field study at Station Nord, Northeastern Greenland, on bromine and Hg chemistry in snow and sea ice. Data analysis is ongoing.
- July – October 2015: Field study aboard the CCGS *Amundsen* from Labrador Sea, Baffin Bay, and the Canadian Arctic Archipelago (CAA) to Canada Basin. In addition to profiling the distribution of total and MeHg in the seawater, incubation experiments were carried out to study the Hg methylation process. Data analysis and interpretation are ongoing.

Pan-Arctic concentrations of mercury and stable isotope ratios in zooplankton

- Assembled new and previously published datasets (Chukchi Sea, Stern et al., 2005; Hudson Bay, Foster et al., 2012; Beaufort Sea (2008), Pucko et al. 2014) of THg and MeHg concentrations and $\delta^{15}N$ and $\delta^{13}C$ ratios in zooplankton for statistical analysis.

Examining Arctic climate fluctuations on mercury concentrations in Ulukhaktok ringed seal (Phoca hispida) using stable mercury isotopes

- Subsampled tissues (muscle, liver, kidney, blubber) of 130 animals from the DFO tissue archive for seals from Ulukhaktok (formerly Holman Island). Samples were taken from two groups: A) three consecutive years with relatively high ice cover (2003-2005; mean ice-free days = 89), and B) three consecutive years with low ice cover (2011-2013, mean ice-free days = 128).
- Analytical procedures for Hg stable isotopic analysis and calculation of mass-dependent and mass-independent fractionation (δ^{202}Hg, Δ^{199}Hg respectively) are in place.

Mercury concentrations in a Beaufort coastal marine protected area

- Community harvesters and junior harvesters from Aklavik and Inuvik, NT, were hired to collect fish samples and record their biometric data. Families from Inuvik and Aklavik also donated some of their catches for the project.
- After samples were shipped to Winnipeg, MB, they were processed by DFO technicians and students for stable isotope and fatty acid data and analysis. Mercury analysis is underway.

Pesticide dynamics at the Ocean-Sea ice-Atmosphere (OSA) interface during winter-summer transition

- Melt-pond water, seawater and air samples (collected in 2012) were analyzed in the lab, followed by statistical analysis and manuscript preparation and submission.

Organophosphate ester flame retardants and plasticizers (OPEs) in the Arctic

- Air, sediment and water (grab and passive) samples were collected from the CCGS *Amundsen* in the summer of 2015 to be analyzed for pesticides, flame retardants and other emerging compounds of concern. The water samples are being used to establish a water monitoring network in the Beaufort Sea. The results of all the samples will be added to the spatial and temporal trends of these compounds in the Canadian Arctic.
- Fourteen OPEs were measured in the particle phase of active air samples from yearly ship-based sampling campaigns (2007 to 2013) to assess the trends and long-range transport potential of OPEs. At least one manuscript including these results was prepared this year.

Polycyclic Aromatic Hydrocarbons in benthic invertebrates from Baffin Bay

- Benthic invertebrate samples were collected aboard the CCGS *Amundsen* cruise in Baffin Bay (summer, 2015).
- Two new laboratory instruments were acquired for hydrocarbon analysis. The first is an automated gel permeation chromatographic system (GPC) which will be used for samples with a high lipid content, effectively separating the hydrocarbons from the lipids. Since a test analyte is n-alkanes, further testing will be done to see if n-alkanes would sufficiently separate from lipids as they are similar in length and mass. The second instrument introduced is a two-dimensional gas chromatography/time of flight mass spectrometer (GCxGC/TOF-MS). The resolution capable from this instrument can yield down to the milli-amu. The machines are being calibrated and tested for accuracy prior to running samples on them.

Interactions between oil and sea ice

- As of January 2016 the artificial mesocosms at SERF have been filled with salt water and facilitated the growth of ice. Control (uncontaminated) experiments have been completed and the addition of crude oil into the tanks will commence shortly. Instrumental procedures and optimization in sample preparation is complete. Results obtained through the course of the experiments will be analyzed accordingly throughout the current year.

RESULTS

Mercury in the High Arctic Ocean and Hudson Bay under a Changing Climate

- At both the Cambridge Bay and SERF mesocosm sites, the molar ratio of Br^-/Na^+ was essentially constant throughout the sea ice depth while the ratio decreased in the upper snow layer, revealing that bromine activation takes place in the snow instead of sea ice. Using Na^+ as a reference ion, our results further suggest that the reactive bromine species observed during the Arctic springtime originate from snow bromide that is derived primarily from non-sea-salt sources.
- Despite high dissolved Hg concentrations in the starting SERF experimental seawater relative to natural marine waters, Hg concentrations in sea ice were similar to those measured in Arctic sea ice. The controlled environmental settings at SERF allowed us to develop a general model to differentiate between the incorporation of particulate Hg into frazil ice and the scavenging of atmospheric Hg in surface crystals.
- Seawater profiling for total Hg in the vast regions of Labrador Sea, Baffin Bay, CAA and Canada Basin showed that Hg concentrations are highly elevated when compared with other regions in the Canadian Arctic Ocean.
- Seawater profiling for MeHg confirmed the ubiquitous occurrence of sub-surface MeHg, which we first reported in Beaufort Sea (Wang et al. 2012). The high resolution profiling also revealed a secondary MeHg peak at the depth corresponding to subsurface chlorophyll maximum (Figure 1).

Pan-Arctic concentrations of mercury and stable isotope ratios in zooplankton

- One of the most striking results from our study is the increased exposure to Hg in the marine food chain of the southern Beaufort Sea. Biomagnification of MeHg between *Calanus* spp. and two of its known predators, *Themisto* spp. and *Paraeuchaeta* spp., was greatest in the southern Beaufort Sea.
- Results indicate large regional variations in stable isotope ratios of $\delta^{13}C$ and $\delta^{15}N$ and Hg concentrations in individual species in relation to regional parameters such as varying water masses and freshwater inputs.

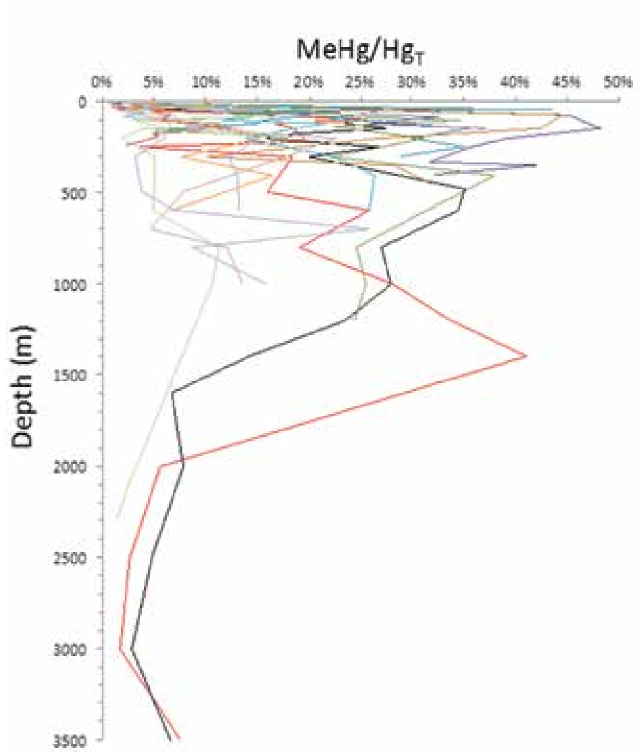

Figure 1. The vertical distribution of the methylmercury-to-total-mercury ratio (MeHg/HgT) in seawater of the Canadian Arctic Ocean. Each colour represents different stations across the Labrador Sea, Baffin Bay, Canadian Arctic Archipelago and Canada Basin. (Kang Wang and Feiyue Wang, unpublished data).

Examining Arctic climate fluctuations on mercury concentrations in Ulukhaktok ringed seal (Phoca hispida) using stable mercury isotopes

- No results to report to date. Analyses of samples will be carried out through the balance of 2015-16 and 2016-2017.

Mercury concentrations in a Beaufort coastal marine protected area

- The dietary biomarker analysis revealed three distinct groups of fishes based on stable isotope signatures and five groups based on fatty acid signatures. Further details can be found in our upcoming publication (Brewster et al. 2016).
- From these groupings, key species of fish representative of pelagic/benthic and nearshore/offshore habitats were selected for total Hg analysis. This analysis will take place over the coming year.

Pesticide dynamics at the Ocean-Sea ice-Atmosphere (OSA) interface during winter-summer transition

- We observed that as melt ponds formed, they accumulated CUPs (e.g. chlorpyrifos, dacthal, trifluralin, pentachloronitrobenzene) and one OCP (α-HCH) from melting snow and sea ice and wet deposition from the atmosphere. Gas phase exchange processes accounted for higher inputs of pesticides to melt ponds as ponds deepened. Once ponds drained into the ocean, so too did the accumulated contaminants.
- CUPs attained higher average concentrations in melt ponds than in snow by a factor of two to five.
- Most OCPs were absent in melt ponds but were detected in snow (concentrations decreased below detection limits before the snow melted into the melt ponds).

Organophosphate ester flame retardants and plasticizers (OPEs) in the Arctic

- Clorinated OPEs (Cl-OPEs) had the overall highest concentrations and detection frequencies with average concentrations of total Cl-OPEs of 209 ± 242 pg m^{-3} and an overall detection frequency of 97%. Tris(chloroethyl)phosphate (TCEP) had the highest individual concentrations of 173 ± 172 pg m^{-3} and 87% detection frequency. Tris(1-chloro-2-propyl)phosphate (TCIPP) had lower average concentrations of 86 ± 101 pg m^{-3} but was detected in 89% of samples. 1,3-dichloro-2-propanol phosphate (TDCPP) was the least abundant Cl-OPE with 5.3 ± 8.3 pg m^{-3} and 75% detection frequency (Figure 2).
- Non-chlorinated OPEs (non-Cl-OPEs) were detected in significantly lower concentrations than Cl-OPEs (Student's t-test at $p < 0.05$) for most compounds. The exception was tri-phenyl phosphate (TPhP), the most abundantly detected non-Cl-OPE with a detection frequency of 90% and concentrations between 0.37-1930 pg m^{-3} (median 7.3 pg m^{-3}) (Figure 2).
- None of the Cl-OPEs showed any significant temporal trends, although TCEP and TDCPP appeared to decrease in concentrations, whereas TCIPP was the only Cl-OPE with a tendency towards slightly increasing concentrations. Concentrations of most non-Cl-OPEs were constant as well, apart from a significant annual increase from 2007-2013 of TPhP by 109% or doubling time of 11 months ($r^2 = 0.65$, $p = 0.044$).

Polycyclic Aromatic Hydrocarbons in benthic invertebrates from Baffin Bay and Interactions between oil and sea ice

- No new results to report to date. Analyses of samples will be carried out through the balance of 2015-16 and 2016-2017.

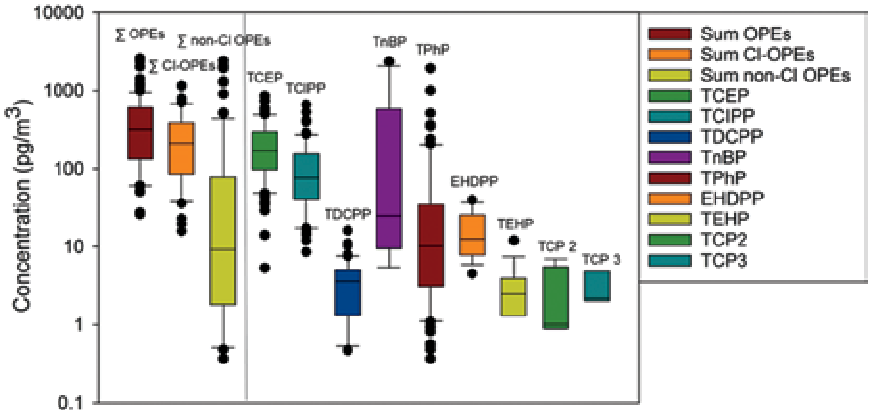

Figure 2. Concentrations (pg m^{-3}) of OPEs in the filter fraction of air samples from the Canadian Arctic (2007 – 2013). Summary of OPEs in panel one and individual compounds in the second panel, displayed are the top nine compounds. The black horizontal line inside each box represents the median. The boxes represent the 25th and 75th percentiles, dots represent outliers. TCEP: tris(chloroethyl)phosphate; TCIPP: tris(chloroisopropyl phosphate; TDCPP: tris(dichloroproyl) phosphate; TnBP: tri-n-butyl phosphate; TPhP: triphenyl phosphate; EHDPP: ethylhexyl dipropyl phosphate; TEHP: tris(ethylhexyl) phosphate; TCP2: tri-m-cresyl phosphate and TCP3: tri-p-cresyl phosphate.

DISCUSSION

Mercury in the High Arctic Ocean and Hudson Bay under a Changing Climate

The large dataset we have accumulated over the past decade from both the field and SERF has provided major insights into the role of the sea ice environment in the transport, transformation and uptake of Hg in the Arctic marine ecosystem.

Pan-Arctic concentrations of mercury and stable isotope ratios in zooplankton

Our results indicate species-specific regional differences in Hg concentrations and isotopic compositions. Hg biomagnification between *Calanus* spp. and *Themisto* spp. was three times greater in the southern Beaufort Sea compared to northern Baffin Bay and four times that of Hudson Bay with similar results between *Calanus* spp. and *Paraeuchaeta* spp. These results highlight the prevalence of Hg biomagnification between various zooplankton trophic linkages and the increased transfer of Hg in the marine food chain within the southern Beaufort Sea (Pomerleau et al., in review). Our findings suggest that increasing levels of Hg in seawater is one of the controlling factors of THg and MeHg concentrations in zooplankton (Pomerleau et al., in review).

Examining Arctic climate fluctuations on mercury concentrations in Ulukhaktok ringed seal (Phoca hispida) using stable mercury isotopes

A recent study by Masbou et al. (2015) has shown that Hg stable isotope signatures were related to extent of ice cover. Their study compared Hg isotopic fractionation in seals collected over several years from two distinct populations where the effect of ice cover was also related to latitude. We feel that our study design will provide a more robust study as our samples are from the same location and population of seals, and our design will also allow us to examine effects of tissue type plus any cumulative effects of high versus low ice cover over several years.

Pesticide dynamics at the Ocean-Sea ice-Atmosphere (OSA) interface during winter-summer transition

Further insight offered by Principle Component Analysis revealed that pesticides that have high average air concentrations, low water solubility and low organic carbon partition potential (such as α-HCH and dacthal) are at the highest risk of reaching high dissolved concentrations in melt ponds due to gas deposition over the summer (Figure 3). Furthermore, relatively water-soluble, larger organic contaminants that are easily scavenged from the atmosphere by snow may load to ponds faster than predicted by gas phase exchange processes due to high initial loadings from melting and falling snow.

Organophosphate ester flame retardants and plasticizers (OPEs) in the Arctic

The higher concentrations of Cl-OPEs compared to non-Cl-OPEs were not surprising. Cl-OPEs are generally more persistent in the environment than non-halogenated OPEs (Verbruggen et al. 2005) and have, historically, been produced and used in larger quantities (van der Veen et al. 2012). Concentrations of halogenated OPEs in this study seemed to be driven by river discharge with the Nelson and Churchill Rivers (MB) and Lake Melville (NT) as sources (Figure 4). In contrast, non-halogenated OPE concentrations seemed to have different sources from long-range transport. OPE concentrations found in this study were in the same order of magnitude as those previously reported by Salamova et al. (2014) and Möller et al. (2012a).

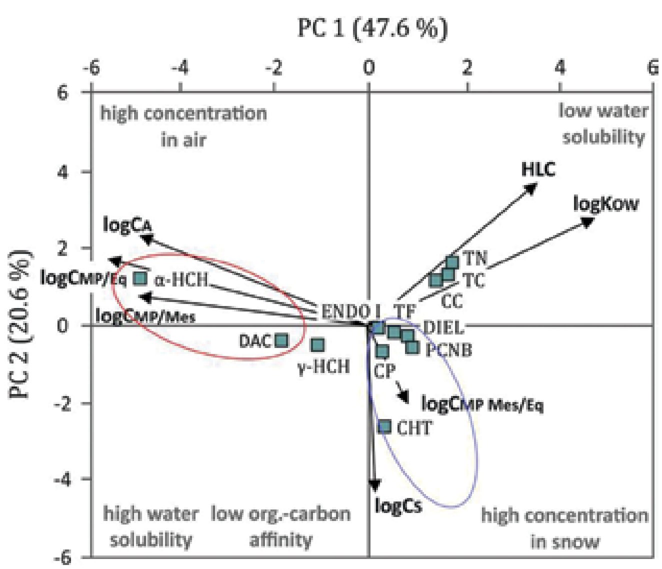

Figure 3. Principal Component Analysis (PCA; correlation matrix) of contaminant scores along with relative loadings of factors (log-transformed prior to analysis).

CONCLUSION

Mercury in the High Arctic Ocean and Hudson Bay under a Changing Climate

Two critical knowledge gaps remaining are 1) the MeHg hotspots; and 2) the process responsible for the production of MeHg in subsurface seawater and sea ice. This will be our main research focus in 2016. Additionally, modeling efforts are needed to project how a changing climate will affect Hg cycling in the Arctic. This will be done jointly with the BaySys and Canadian Arctic GEOTRACES programs.

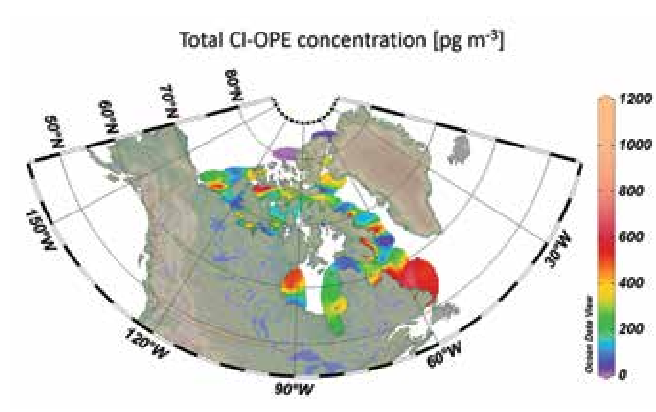

Figure 4. Geographic distribution of total Cl-OPEs (TDCPP + TCEP + TCPP) [pg m^{-3}] in air-borne particles from the Canadian Arctic, 2007-2013.

Pan-Arctic concentrations of mercury and stable isotope ratios in zooplankton

In summary, our research suggests that zooplankton play an important role in the Hg pathway within marine food webs. However, far too little is known about the processes and mechanisms concentrating and bioaccumulating Hg within zooplankton. Future work is needed to understand spatial variation in zooplankton Hg concentrations by relating these to regional processes including atmospheric deposition, riverine supply, sea-ice formation and melting and methylation/demethylation.

Pesticide dynamics at the Ocean-Sea ice-Atmosphere (OSA) interface during winter-summer transition

CUPs are at a relatively high risk of reaching high concentrations in melt ponds over the summer (Pućko et al. 2015), a process ultimately determined by gas exchange. Since CUP presence in the Arctic air is highly dynamic, possibly periodic, and dependent on various factors (e.g. season, horizontal and vertical motion of the atmosphere), loading of particular CUPs to melt ponds may differ temporally and spatially over the Arctic Ocean.

Organophosphate ester flame retardants and plasticizers (OPEs) in the Arctic

The detection and significant increasing concentrations of non-Cl-OPEs, and especially TPhP, in the Arctic Ocean (Möller et al. 2012a), Canadian (this study) (Jantunen et al. 2014) as well as European Arctic (Salamova et al. 2014) raises questions whether non-Cl-OPEs are indeed suitable replacements for brominated flame retardants from an environmental perspective.

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Mercury in the High Arctic Ocean and Hudson Bay under a Changing Climate

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Pan-Arctic concentrations of mercury and stable isotope ratios in zooplankton

Samples were collected in part by ArcticNet, the Beaufort Regional Environmental Assessment (BREA), the Circumpolar Flaw Lead Study (CFL), the Nansen and Amundsen Basins Observation System (NABOS), Études des Mers Intérieures du Canada (MERICA) and the Surface Heat Budget of the Arctic (SHEBA). We thank Fisheries and Oceans Canada, Canada's Northern Contaminants Program, the Natural Sciences and Engineering Research Council of Canada and the Canadian Foundation for Innovation. We also thank J. DeLaronde, D. Armstrong, A. MacHutchon, W. Walkusz, G. Boila, A. Burt, J. Carrie, C. Lalande, G. Darnis, M. Ringuette, L. Létourneau and many others for their help with collecting and sorting the samples. We are grateful to the officers and crew of the CCGS *Amundsen*, *Pierre Radisson*, *Des Groseilliers* and the Russian icebreaker *Kapitan Dranitsyn*. C. Pomerleau was supported by a W. Garfield Weston Postdoctoral fellowship.

Examining Arctic climate fluctuations on mercury concentrations in Ulukhaktok ringed seal (Phoca hispida) using stable mercury isotopes

We acknowledge the support of DFO – Freshwater Institute for allowing us access to archived tissue samples of ringed seals from Ulukhaktok.

Mercury concentrations in a Beaufort coastal marine protected area

We gratefully acknowledge the funding agencies for this project, including AANDC, FJMC, the Inuvik and Aklavik HTCs, DFO and BREA. Special thanks to T. Loewen for setting up the Shingle Point field program, the Aklavik HTC (especially M. Gruben), monitors J. Mcleod, D. Arey, C. Kogiak, and C. Greenland, Aklavik and Inuvik Community members, DFO Inuvik staff E. Lea, L. Dow, E. Wall, and S. Fosbery, DFO Winnipeg staff J. Reist, C. Gallagher, K. Howland, S. Cloutier, A. Majewski, W. Wallkusz, R. Banjo, B. Rosenberg, D. Neumann, C. Morrison (UofA), and FJMC staff K. Hynes and D. Swainson.

Pesticide dynamics at the Ocean-Sea ice-Atmosphere (OSA) interface during winter-summer transition

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Organophosphate ester flame retardants and plasticizers (OPEs) in the Arctic

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Polycyclic Aromatic Hydrocarbons in benthic invertebrates from Baffin Bay

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Arc3Bio (Marine Biodiversity, Biological Productivity and Biogeochemistry in the Changing Canadian Arctic)

Project Leaders

Jean-Éric Tremblay (Université Laval); Philippe Archambault (Université du Québec à Rimouski); Michel Gosselin (Université du Québec à Rimouski)

Network Investigators

Simon Bélanger (Université du Québec à Rimouski)
Jay Cullen (University of Victoria)
Dany Dumont (Institut des sciences de la mer de Rimouski)
Connie Lovejoy (Université Laval)
Frédéric Maps (Université Laval)
Christian Nozais (Université du Québec à Rimouski)
Michel Poulin (Université du Québec à Rimouski)
Soren Rysgaard (University of Manitoba)

Collaborators

David G. Barber (University of Manitoba)
Nicolas Cassar (Duke University)
Julie Granger (University of Connecticut)
Maurice Levasseur (Québec-Océan)
CJ (Christopher John) Mundy (Université du Québec à Rimouski)
Feiyue Wang (University of Manitoba)

HQP

Aboyo Essi Enyonam, Doctoral Student (Institut des sciences de la mer de Rimouski, UQAR)
Blandine Gaillard, Doctoral Student (Université du Québec à Rimouski)
Analyse structurelle et potentiel paléoclimatique d'Astarte moerchi dans l'Arctique Canadien
Gwenaëlle Gremion, Doctoral Student (Institut des sciences de la mer de Rimouski, UQAR)
Nathalie Jolie, Doctoral Student (Université Laval)
Metagenomics, genomics and transcriptomics of Arctic phytoplankton species
Christian Marchese, Doctoral Student (Université du Québec à Rimouski)
Physical controls on seasonal and inter-annual variability of phytoplankton biomass and primary production of arctic and subarctic marine regions: a novel satellite-based approach
Deo Florence Onda, Doctoral Student (Université Laval)
Biodiversity of Arctic phytoplankton
Arnaud Pourchez, Doctoral Student (Université Laval)
Nicolas Schiffrine, Doctoral Student (Université Laval)
Nutrient cycling in Arctic marine ecosystems
Armelle Simo, Doctoral Student (Université du Québec à Rimouski)
Variabilité spatiale et temporelle des communautés bactérienne et phytoplanctonique dans les fjords subarctiques de la côte Est du Canada
Marie-Claude Bourboin, Honours Undergraduate Student (Université du Québec à Rimouski)
Sébastien Guérin, Honours Undergraduate Student (Université du Québec à Rimouski)
Gonzalo Bravo, Masters Student (Université du Québec à Rimouski)
Vincent Carrier, Masters Student (UNIS - The University Centre in Svalbard)
Biogeography of marine pico- and nanoeukaryotes around Svalbard Archipelago, Norway

Joannie Charette, Masters Student (Université du Québec à Rimouski)
Jean-Sébastien Côté, Masters Student (Université Laval)
Isabelle Courchesne, Masters Student (Université Laval)
Noémie Friscourt, Masters Student (Université du Québec à Rimouski)
Julien Laliberté, Masters Student (Université du Québec à Rimouski)
Validation d'un modèle de production primaire satellitaire pour l'océan Arctique : éclairement incident et réflectance marine
Solveig Bourgeois, Post-Doctoral Fellow (University of Aberdeen)
Pierre Coupel, Post-Doctoral Fellow (Université Laval)
Clémence Goyens, Post-Doctoral Fellow (Université du Québec à Rimouski)
Mary Thaler, Post-Doctoral Fellow (Université Laval)
Gabrièle Deslongchamps, Research Associate (Institut national de la recherche scientifique - Institut Armand-Frappier)
Cindy Grant, Research Associate (Université du Québec à Rimouski)
Marianne Potvin, Research Associate (Université Laval)
Marjolaine Blais, Technical Staff (Université du Québec à Rimouski)
Sylvain Blondeau, Technical Staff (Québec-Océan)
Laure de Montety, Technical Staff (Institut des sciences de la mer de Rimouski)
Jonathan Gagnon, Technical Staff (Université Laval)
Virginie Galindo, Technical Staff (Université Laval)
Pascal Guillot, Technical Staff (Québec-Océan)
Sylvie Lessard, Technical Staff (Institut des sciences de la mer de Rimouski)
Michèle Pelletier-Rousseau, Technical Staff (Institut des sciences de la mer de Rimouski)
Lisa Treau de Coeli, Technical Staff (Institut des sciences de la mer de Rimouski)
Gabriel Ladouceur, Undergraduate Student (Université du Québec à Rimouski)

ABSTRACT

Arctic marine ecosystems provide numerous benefits and services of economic, societal and ecological value, including the provision of food resources, the conservation of biodiversity, carbon storage and nutrient recycling, among others. The Arc3Bio project combines the multidisciplinary skills of several experts to evaluate how climate variability and change, as well as direct human influence, affect the sensitivity and resilience of ecosystem functions and services at a variety of scales. Addressing different scales is necessary because the Arctic has strong connections with peripheral oceans and rivers. Variability and change at the regional scale, which is the focus of ArcticNet's Integrated Regional Impact Studies, can only be understood if external forcing at the boundaries is taken into account, and if the cumulative impacts of smaller-scale processes that shape biodiversity and biogeochemistry in different key areas are known. To do so we use an innovative combination of complementary approaches based on direct measurements from the CCGS *Amundsen* and other ships, remote observations of ocean color by orbiting satellites, and controlled experiments with samples from the water column and the seafloor. We pay special attention to the impact of changing light conditions and nutrient supply (especially nitrogen) on biological productivity and the contribution of different types of micro-algae that can be viewed as "good or bad" for the sustenance of zooplankton and the herbivorous food web. We also investigate how changing contributions of ice algae and phytoplankton to total primary production are likely to affect the benthic organisms living on the sea floor. Finally, coupled physical-biological numerical models are implemented to generate plausible futures for the productivity and structure of the lower marine food web, using climate projections made by Ouranos for 2025, 2050 and 2100. The results of our work is communicated though various means to stakeholders and communities (e.g. Regional Impact Assessment reports), the general public and the broader science community.

KEY MESSAGES

In order to shorten our report this year, we have divided key messages into two categories that pertain to 1) the results described in detail in the following sections and 2) other important works not described in detail (bullet points).

Key Messages (emanating from the results presented)

- The overall biological productivity of Arctic waters is determined by a combination of local events (e.g., ice dynamics and vertical mixing) and remote processes linked to the global ocean circulation and imbalanced nitrogen cycling.
- Productivity is generally low in the Canadian Arctic due to the strong denitrification occurring in distant regions, from the North Pacific Ocean to the shallow sediments of the Chukchi Sea.
- Remote sensing data showed a decline in total annual primary production (PP) of the North Water polynya from 1998 to 2010. Positive trends in PP in May and negative trends for the rest of the summer season also suggest a change in the seasonal timing of phytoplankton production caused by shifting ice dynamics.
- Warmer winters, indicated by lower cumulative freezing degree-day values, cause the ice bridge located in Nares Strait to break-up earlier, leading to early seasonal loss of integrity for the North Water polynya.
- Climate, sea ice and ocean colour indicators suggested that temporal and spatial shifts in the pelagic primary productivity induced by changes in the ice bridge dynamics could explain the observed trends and may dramatically affect benthic species.
- Estimates of biological nitrogen (N) fluxes (e.g. fixation, assimilation and recycling) in Arctic sea ice suggest that N cycling is roughly balanced and that sea ice does not provide a net N source (e.g.,

through nitrogen fixation) that could compensate for denitrification in remote waters. Deliveries of nitrogen by rivers are also insufficient to significantly counteract denitrification.

- Seasonal variations in phytoplankton dynamics in four Labrador fjords are controlled by the strength of the vertical stratification, which limits nutrient supply, and by the large differences in day length resulting from latitude.
- The assessments of phytoplankton structure and function in Labrador fjords provided an essential foundation for future monitoring of environmental change in coastal subarctic areas.
- Stable isotopes and sea ice biomarkers IP_{25} data allowed us to define trophic redundancy, trophic separation, and community niche space of benthic food webs.

Other key messages

- The implantation of a novel framework based on the combined use of satellite cloud-free chlorophyll images and Gaussian models contributed to better describe the seasonal timing of phytoplankton production in Arctic waters (Marchese et al. In prep.).
- The evaluation of two satellite-based methods (Bélanger et al. 2013; Frouin et al. 2003) to estimate photosynthetically active radiation in the Arctic Ocean indicated that both methods have a relative uncertainty larger than that observed at low latitude (Laliberté et al. Submitted).
- In ice-infested waters, an alternative method of atmospheric correction for satellite ocean color data, which we developed, works better than the standard approach (Goyens et al. In prep).
- The Bélanger et al. (2013) algorithms presented to the Primary Productivity Algorithm Round Robin (PPARR) were among the best in terms of performance against sea truth. This comparison indicates that general models need to be carefully tuned for the Arctic Ocean since the best ones use Arctic-specific parameterizations (Lee et al. 2015).
- A compilation of existing time-series data on ice algae contributed to the first pan-Arctic understanding of the most important factors controlling the development and termination of vernal ice-algal blooms (Leu et al. 2015).
- Weather events that rapidly melt the snow cover can significantly deplete chlorophyll *a* in bottom sea ice and cause early termination of the ice-algal bloom in late spring (Campbell et al. 2015).
- Irradiance and temperature influence the viability and photosynthetic performance of surface phytoplankton communities in the Canadian Beaufort Sea during the spring-summer transition (Alou-Font et al. In press).
- A study of mycosporine-like amino acids (MAAs) synthesized by algae improved our knowledge of photo-acclimation and photoprotection against UV radiation in algal communities (Elliott et al. 2015; Alou-Font et al. In press).
- Springtime experiments performed with phytoplankton assemblages provided additional evidence for the existence of under-ice phytoplankton blooms in Arctic waters (Galindo et al. 2015; 2016).
- The high contribution of the heterotrophic dinoflagellates *Gymnodinium* and *Gyrodinium* spp. to total carbon biomass in the Beaufort Sea during summer suggest that microbial grazing activity is high at this time of the year (Coupel et al. 2015).
- Surveys of megabenthic communities across the western and eastern Canadian Arctic showed that distinct benthic food web structures prevail over shelf and slope environments and provided new evidence for the importance of ice algae as a carbon source for benthic organisms (Roy et al. 2015).
- Forcing the DARWIN (MIT) model with Environment Canada's CREG12 data improves simulations of emerging phytoplankton functional types (PFTs) in the Canadian Arctic.

OBJECTIVES

Central objectives for Arc3Bio during ArcticNet phase IV

- To build on the expertise of a successful team to better quantify, understand, synthesize and anticipate variability and change in the productivity, biodiversity and biogeochemical functions of the lower marine Arctic food web.
- To address major knowledge gaps through three interconnected work packages focusing on the assessment and prediction of variability and change (ArcTrends) as it relates to alterations of nitrogen supply (NitrArc) and the diversity of species, communities and functions in the lower food web (DiveArc).

Specific objectives

- To implement numerical ecosystem models and extend time-series of observations beyond the decadal time scale to better constrain the physical drivers of variability and change in primary production and different functional types of phytoplankton, ensuring that long-term ArcticNet time series yield their full benefits (ArcTrends).
- To augment our quantitative understanding of N supply and cycling in the water column and the benthos and their cumulative impacts on the biological productivity of waters flowing through the Canadian Archipelago, from the Beaufort Sea to the Labrador Sea (NitrArc).
- To advance biodiversity surveys of planktonic microbes and benthic communities and elucidate linkages between this diversity, biological productivity and ecosystem functions (DiveArc).

INTRODUCTION

At the base of the food web, the photosynthetic primary production (PP) of organic matter (OM) by ice algae and different functional types of phytoplankton (PFTs) responds rapidly to changes in the availability of light, nutrients and other growth factors. This response conditions the productivity of harvestable resources since the intensity of PP by different PFTs sets an upper limit to the quantity of OM available to feed consumers higher up the food web (e.g. Bessière et al. 2007, Chassot et al. 2007). In parallel, the contraction of frozen habitats directly challenges organisms that depend on sea ice for nutrition, refuge or reproduction. Climate-driven decreases in the size and range of their populations along with invasions by temperate species will reshape biodiversity and ecological interactions, with effects rippling up and down the food web.

Primary producers affect global inventories of climate-active and life-sustaining gases. Photosynthesis keeps our air breathable by splitting oxygen (O_2) from water. Marine microalgae mitigate warming by releasing dimethylsulfide (DMS) and fixing carbon dioxide (CO_2) into biomass. When a portion of this biomass and derived detritus sinks beneath the surface, carbon atoms formerly bound in atmospheric CO_2 are transported downward. Variable proportions of this carbon are stored in deep waters, consumed by the benthic fauna or consigned to the sediment. The size and efficiency of this "biological CO_2 pump" depends on several factors (e.g., intensity of PP and dominance by different PFTs, community respiration, pH) that respond to the changing environment (e.g. Sabine and Tanhua 2010). The OM synthesized by algae and transiting through the food web must ultimately be decomposed and re-circulated to keep the finite reservoir of nutrients available. Altered rates and pathways of nutrient cycling by pelagic and benthic microbes and consumers can therefore have a large cumulative impact on PP in the Arctic.

ArcTrend - Monitoring long-term trends in phytoplankton PP is crucial to understand how physical changes affect the Arctic environment. Satellite remote sensing of PP remains the only way to track change in the biological productivity of the ocean at relatively high temporal (daily) and spatial scales (~ 1-km). Recent data point toward major shifts in the spatial distribution and productivity of biological hotspots across the Canadian Arctic and beyond. While PP increases in some sectors, it remains stable in some and even decreases in others. The shifts in PP are likely to result from changing ice-arch dynamics (e.g. Nares Strait). Using an eddy-resolving model, Dumont et al. (2009, 2010) explained ice-arch formation and how it affects circulation and nutrient transport, fluxes of heat and freshwater, vertical stability and upwelling. The understanding of this phenomenon and its impacts on the ecosystem comes from the sustained research efforts of the past decades, to which many NIs of this project has contributed. The trends observed from remote-sensing, modeling and nutrient drawdown provide an integrated measure of change for the entire growth season, but need to be compared with direct, discrete observations of phytoplankton production, biomass and taxonomic composition. This detailed data provides a necessary perspective on the environmental factors causing the change in a given area.

NitrArc - The availability of nitrogen (N) in the upper euphotic zone is the primary determinant of annual PP in seasonally ice-free Arctic waters (Tremblay et al. 2015), whereas light availability mostly controls the timing and vertical horizon of this PP. Nitrogen (N) supply exerts a major control on PP in the water column as well as in the seasonal sea ice of the Arctic Ocean. Sea ice, which is a key constituent of the Arctic ecosystem and provides unique habitats for a host of microbes and small grazers, is rapidly thinning and transitioning toward a predominantly seasonal cover of first-year ice. This report provides the first assessments of biological N fluxes in landfast ice.

DiveArc - Ecosystem functions and services are linked to the diversity of active microbes, algae and consumers that compose the lower food web. Ongoing changes in the physical Arctic environment alter biodiversity in several ways, including shifts in species dominance and community structure, extinctions and invasions that affect major biogeochemical functions, including N cycling, PP, pelagic-benthic coupling and carbon storage. Potential impacts of climate change and human activities on the trophic structure and resilience of benthic food webs in the Arctic are still difficult to assess because of the lack of baseline data. In this year's report, we document how the ongoing changes in the Arctic may affect the intensity and spatial distribution of PP and the nature of pelagic-benthic coupling. This could disturb the amount and quality of OM that settles onto the seafloor, and the benthic communities that feed upon it.

ACTIVITIES

Dissemination of scientific results

- Wide dissemination of results to the scientific communities, public, partners and stakeholders in high-ranking articles submitted (5), accepted and/or published (23), invited talks (4), oral presentations (12), poster presentations (22), MSc dissertations (2), PhD defense (1), book chapters (4) and reports (2).
- Participation to national/international conferences: AGU Fall meeting (San Francisco, California, USA), 49th CMOS Congress & 13th AMS Conference on Polar Meteorology and Oceanography (Whistler, Canada), 11th ArcticNet Annual Scientific Meeting (Vancouver, Canada), 14th General Meeting of Québec-Océan (Québec, Canada), NETCARE workshop 2015 (Toronto, Canada), SOLAS Conference (Kiel, Germany), ASSW 2015 Ocean Science Meeting (Toyama, Japan), Ocean Sciences Meeting/ASLO 2016 (New Orleans, USA), Arctic Frontiers 2016 (Tromsø, Norway).

- Participation to science and data workshops: Kolartic ENPI CBC (Pasvik, Norway), Baffin Bay - Adaptation Actions for a Changing Arctic Baffin Bay & Davis Strait Regional Assessment (Aarhus University, Frederiksborgvej, Danemark), 1st Netcolor workshop (Saint-Hubert, Canada), WOMS 2015 (Sopot, Poland), Carbon Bridge 2016 Annual Meeting (Sommaroy, Norway), Arctic Response Technology, Oil Spill Preparedness (Coppenhagen, Denmark), SUBICE project (Québec City, Canada), GreenEdge planning workshop (Paris, France), AN OCB Scoping Workshop (Waterville Valley, USA).
- Invited speaker (S. Bélanger and C. Goyens) at the 1st Netcolor workshop (Saint-Hubert, Canada).
- Invited speaker (S. Bélanger) at International Workshop on Organic Matter Spectroscopy (WOMS) 2015 (Sopot, Poland).
- Presentation (S. Bélanger) of the IOCCG report on Ocean Colour Remote Sensing in Polar Seas at the 21st annual meeting of the International Ocean Colour Coordinating Group (Paris, France).
- Presentation (F. Maps) of numerical modelling results about Arctic copepod communities at a workshop entitled “Trait-based approaches to ocean life” (Waterville Valley, USA).
- Contribution to the section Arctic Ocean Primary Production of the Arctic Report Card 2015 of the National Oceanic and Atmospheric Administration (NOAA).
- Best poster awards to I. Courchesne at the 14th General Meeting of Québec-Océan (Québec, Canada) and 11th ArcticNet Annual Scientific Meeting (Vancouver, Canada).
- Redaction and submission of the Marine Ecosystem chapter for the AACA (Adaptation Actions for a Changing Arctic, led by AMAP) report on the Baffin Bay/Davis Strait region.

Field work

- Participation to the ArcticNet/Geotraces joint CCGS *Amundsen* expedition from July to November 2015 (P. Archambault, M. Blais, S. Bourgeois, V. Carrier, J. Charette, I. Courchesne, L. de Montety, G. Deslongchamps, J. Gagnon, V. Galindo, C. Grant, C. Lovejoy, M. Pelletier-Rousseau).
- Participation to the BIO-DFO CCGS *Hudson* expedition in the Labrador Sea as part of the VITALS project in May 2015 (S. Bélanger, I. Courchesne, G. Deslongchamps, C. Marchese).
- Participation to a cruise onboard the RV *Martin Bergmann* to characterize the hard bottom communities living on and around the HMS *Erebus* wreck in August 2015.
- Participation to the GreenEdge project ice camp located near Qikiqtarjuaq, Baffin Island, from March to June 2015.
- Installation and recovery of two autonomous camera systems in Eclipse Sound.
- Invited participation to a survey in North-West Iceland to collect benthic samples in October 2015.
- Participation to a survey in South-West Greenland to collect benthic samples from May to June 2015.
- Collaboration with M. Ringuette from BIO-DFO (Dartmouth, Canada) for the collection of phytoplankton samples in Davis Strait in September-October 2015.
- Participation to the German-led TRANSSIZ expedition on board the RV *Polarstern* in the Eurasian Arctic (June-July 2015).
- Participation to an experimental mesocosm study of the impacts of oil spills and response actions on first-year sea-ice (Joint industry project funded by the International association of oil and gas producers).

Laboratory work, instrumentation, analysis

- P. Archambault's team are processing benthic samples for stable isotopes, IP_{25} and biodiversity analyses from the 2015 ArcticNet cruise.
- S. Bélanger's team is processing the in-water optical measurements carried on during the 2013 and 2014 ArcticNet cruises.
- J.-É. Tremblay's team processed the samples collected during the 2014 and 2015 ArcticNet cruises and the TRANSSIZ expedition.
- S. Bélanger completed the laboratory analyses of particulate absorption samples collected in the Baffin Bay during the 2014 ArcticNet cruise.
- J. Charette (MSc student) evaluated the contribution of algal communities developing in melt ponds.
- A. Simo-Matchim (PhD student) analyzed the fate of primary production in Labrador fjords based on a simulated *in situ* grazing experiment.
- N. Shiffrine continued his work with laboratory cultures of algal species that dominate subsurface chlorophyll maxima in the Arctic Ocean.

HQP training

- One PhD student has successfully defended their thesis (B. Gaillard).
- Two MSc students handed in their dissertations and graduated (J. Laliberté and J.-S. Côté).
- One PhD student (A.G. Simo-Matchim) and two MSc students (J. Charette, N. Friscourt) are writing up their theses.
- One PhD student (A. Pourchez) has successfully passed his doctoral exam and will be presenting his project by next April.
- Two new MSc students were recruited (G. Bravo; started in September 2015, A. Boivin; will start in May 2016).
- One MSc student spent five weeks at the SCRIPPS Institution of Oceanography in the laboratory of Dr. R. Frouin to work on PAR algorithms evaluation (J. Laliberté).
- Two undergrad students were involved in Arctic research under the framework of the GreenEdge 2014 project (M.-C. Bourboin, S. Guérin).
- Two trainees onboard the CCGS *Amundsen* (leg 3a: M. Pelletier-Rousseau; leg 4ab: V. Gallindo).

Other activities

- Archival of data collected from 2007 to 2013 in the Labrador fjords on phytoplankton community in the Polar Data Catalog (A.G. Simo-Matchim).
- M. Blais and V. Galindo participated in the Schools on Board program during leg 4 of the ArcticNet expedition (1-11 October 2015). Participants to the program included one Inuit student from Pond Inlet.
- Postdoctoral fellow (C. Dufresne) is working on an upstream modeling project funded by the W. Garfield Weston Foundation.

RESULTS

Satellite observations and primary production time series in Baffin Bay and Labrador Sea (NI: S. Bélanger; HQP: C. Goyens, C. Marchese). Contribution to ArcTrends.

Based on the analyses of satellite data (SeaWiFS) for the period 1998 to 2010, Bélanger et al. (2013) showed that the positive impact of reduced sea ice on light penetration and PP can be offset by increased cloudiness over open waters. While PP increases in most Arctic waters, it remains stable in some and even decreases in others, such as in the northern part of Baffin Bay. This year we have extended our satellite-derived PP time series to 2014 using MODIS-Aqua data (2003-2014) for the Baffin Bay and Labrador

Sea. The satellite time series from SeaWiFS and MODIS-Aqua were merged after adjusting the PP rates of one of the sensor to the other based on the period where both satellites provided data of good quality (i.e. 2003-2008). The PP time series of eight known hotspots distributed along the coasts of Greenland and Baffin Island were examined: Hudson Strait, Hatton Basin, Lancaster Sound, Smith Sound, Greenland Shelf from Uummanaq to Melville, Disko Bay, Store Hellefiskebanke, Manitsoq area and Fyllas Bank (Figure 1). Locally, the highest increase in annual PP occurred over the Greenland Shelf, in Baffin Bay and especially in the Labrador Sea (Figure 1e to h). For the latter, this pattern agrees with the results of a 20-year long ship-based survey of the AR7W transect between Labrador and South Greenland (Li and Harrison 2014). These authors documented a particularly important

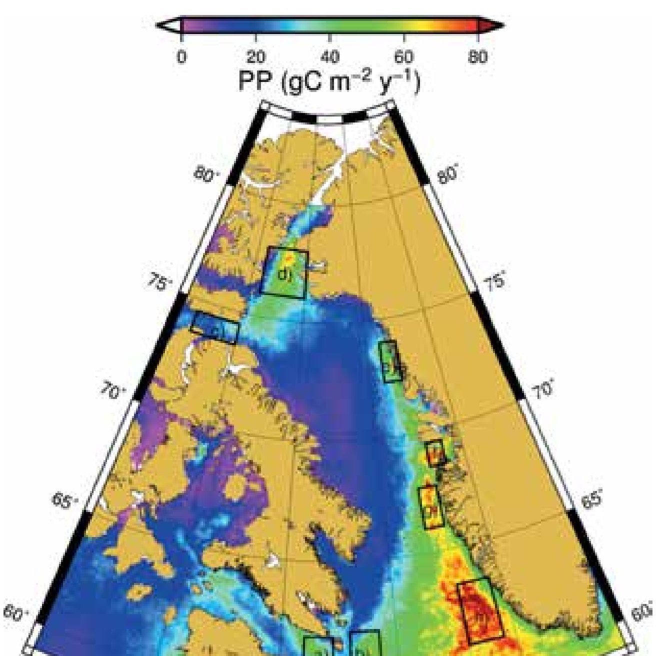

Figure 1. Annual primary production in the eastern Canadian Arctic derived from MODIS-Aqua data. Boxes are drawn around eight marine hotspots for which PP time series were analysed: (a) Hudson Strait, (b) Hatton Basin, (c) Lancaster Sound, (d) Smith Sound, (e) Greenland Shelf from Uummanaq to Melville, (f) Disko Bay, (g) Store Hellefiskebanke, and (h) Manitsoq area and Fyllas Bank.

rise of chlorophyll *a* concentrations on the Greenland shelf and slope between 1994 and 2013. Collectively, these studies imply that the positive effect of reduced sea ice on the availability of solar irradiance and/or nutrient supply outweighed the potentially negative impact of enhanced vertical stratification in these areas. In contrast to Baffin Bay, productivity in the central and eastern Labrador Sea has been decreasing in recent years (e.g. Figure 2b). The 17-years satellite time series, however, revealed that decadal oscillations might overlap the long-term trend in annual PP in many regions (e.g., Figure 1g and h). Those oscillations may be driven by large-scale atmospheric and oceanic circulation variability patterns, but satellite time series are still too short to distinguish the decadal oscillation from secular trends in PP. For example, the updated PP time series of the North Water shows that productivity has been increasing again in recent years and possibly follows a cyclical pattern (Figure 2d), since the inclusion of data from 2011-2014 terminates the negative trend.

Ice arching formation process at the southernmost end of Nares Strait (NI: D. Dumont; HQP: G. Gremion). Contribution to ArcTrends.

Ice arching is a key dynamical process with profound implications on marine ecosystems. The most prominent and documented one is the ice arch that forms recurrently at the southernmost end of Nares Strait from which origins the North Water polynya. Of particular interest are the results obtained from a multidisciplinary and international study of the growth of a bathyal shell collected in the North Water. Schlerochronology data show a significant positive anomalous growth rate over the last decade of the time series (ca. 2000-2010; Figure 3a) and only the variability of the pelagic phytoplankton as a food source can explain these trends (Gaillard et al. Submitted). Climate, sea ice and ocean colour indicators suggest that temporal and spatial shifts in the pelagic primary productivity induced by changes in the ice bridge life cycle could explain the observed trends, but also that changes in the upper ocean may

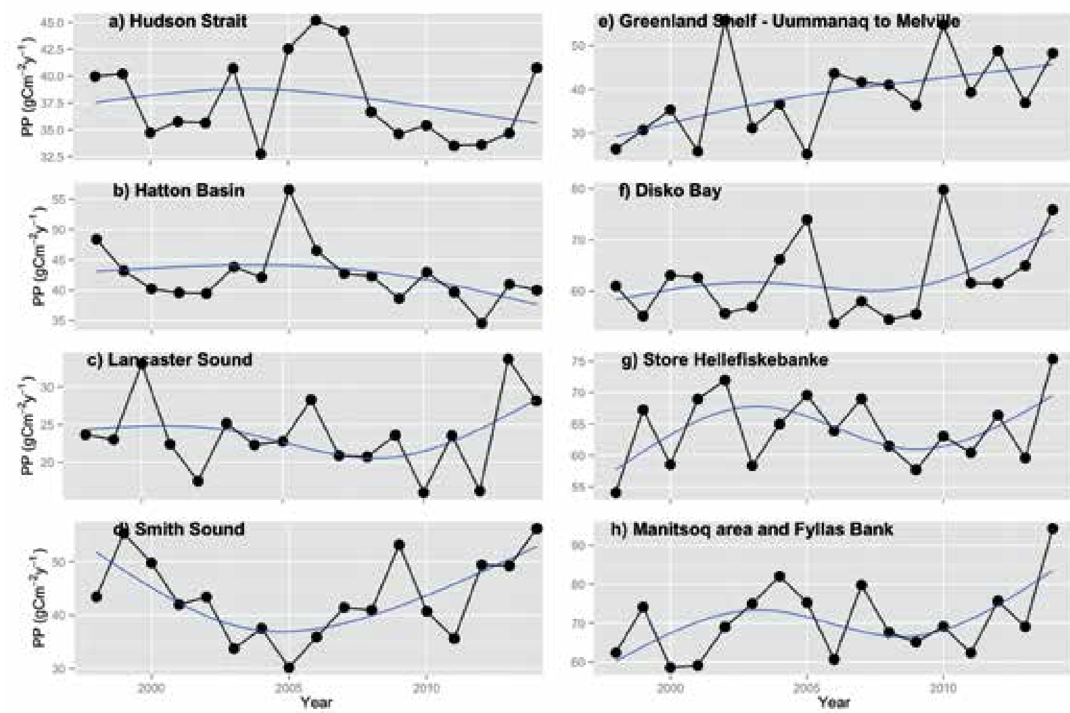

Figure 2. Time series of primary production for the eight marine hotspots shown in Figure 1.

affect dramatically the benthic species as deep as 600 m. Warmer winters, indicated by lower cumulative freezing degree-day values, cause the ice bridge to break-up earlier (Figure 3b, the red curve corresponds to the Nares Strait ice arch break-up week), which determine when, where and how much light penetrates the ocean. Causal relations have not been identified yet, but these results pose interesting and intriguing questions that are currently addressed by the PhD candidate G. Gremion using 3D coupled ice-ocean-biogeochemical modeling (Gremion et al. 2015), a project showing the strong connectivity between the three Arc3Bio components.

Two camera systems have been installed in Eclipse Sound, Nunavut, to monitor the ice cover break-up, a marine biological hotspot and a key travel and harvesting area for the community of Pond Inlet (Mittimatalik). This research was conducted after a spontaneous collaboration between D. Dumont and C. Debicki (Oceans North Canada) following discussions at the 2013 Nuuk meeting. The rationale behind this project is to document the natural break-up of the landfast ice in the Sound (Figure 4) before extensive icebreaking happens if the Mary River iron ore mine extension project is granted.

Global and regional drivers of nutrient supply, primary production and CO_2 drawdown in the changing Arctic Ocean (NI: J.-É. Tremblay, S. Bélanger; HQP: P. Coupel). Contribution to NitrArc and ArcTrends.

To better understand how biological productivity in Canadian waters and the Arctic in general is influenced by processes operating at different scales of time and space, we assembled an international team and combined historical data and ArcticNet data to assess the main environmental factors driving spatial patterns, variability and change in PP in the Arctic Ocean. While instantaneous PP rates are predominantly influenced by the local factors affecting light penetration through

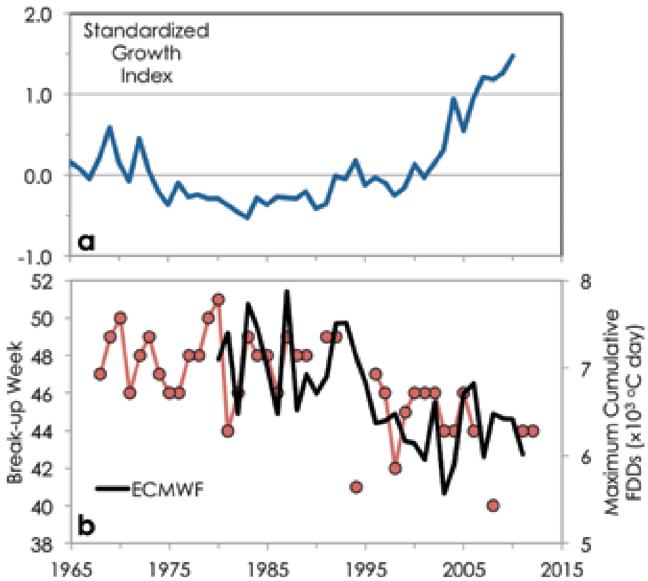

Figure 3. (a) The Standardized Growth Index (SGI) of Astarte moerchi bivalve shells collected in the North Water and (b) break-up week of the Nares Strait ice arch and the maximum cumulative number of freezing degree-days (FDDs), an indicator of winter's severity, calculated from ERA-Interim 2-m air temperature data.

clouds, sea ice and water, net PP (NPP) at the annual scale is conditioned by a hierarchy of remote and local processes that affects nutrient supply and light availability in general. Nutrient supply sets spatial differences in realized or potential trophic status (i.e. oligotrophic or eutrophic), whereas light availability modulates PP within each regime. Horizontal nutrient supply through Atlantic and Pacific ocean gateways differ markedly, which is explained by their position at opposite ends of the global meridional overturning circulation and imbalanced nitrogen (N) cycling in the Pacific sector. Horizontal nutrient inputs to the surface Arctic Ocean are eventually transferred to the halocline through winter convection and the decomposition of settling organic matter. The subsequent re-injection of these nutrients to the euphotic zone varies by two orders of magnitude across sectors, depending on the strength and persistence of the vertical stratification. Such differences in nutrient delivery are commensurate with those of estimated PP and NPP rates. Figure 5 shows the propagation of phosphate-rich water from

Figure 4. Image taken by one of the camera during the Eclipse Sound ice break-up on 18 July 2015.

Bering Strait to the Canadian Arctic via the halocline. These waters are N limited due to denitrification in the oxygen minimum zones of the North Pacific and anoxic sediments of the Bering and Chukchi seas. The severity of this N limitation is given by the parameter N*, which estimates how much additional nitrate would be required to allow the phytoplankton to use all the phosphate available (see Tremblay et al. 2015 for definitions).

Biological nitrogen fluxes in Arctic sea ice during the spring ice-algal bloom (NI: J.-É. Tremblay; HQP: J.-S. Côté, J. Gagnon). Contribution to NitrArc.

The main objective of this study was to assess spatial variability of N cycling processes in bottom sea ice, including the assimilation of nitrate (NO_3^-) and ammonium (NH_4^+), N_2 fixation, ammonification and nitrification and how this variability relates to broadly ranging environmental conditions. To do so, bottom ice samples collected in the eastern Canadian Arctic Archipelago during the 2013 spring ice-algal bloom were incubated with ^{15}N tracer. The results show a high variability in all the N fluxes measured (Figure 6), which mostly relates to the accumulation of chlorophyll *a* and prokaryotes (Côté 2015). Allowing for some methodological uncertainties, the assimilation of NH_4^+ by organisms is roughly

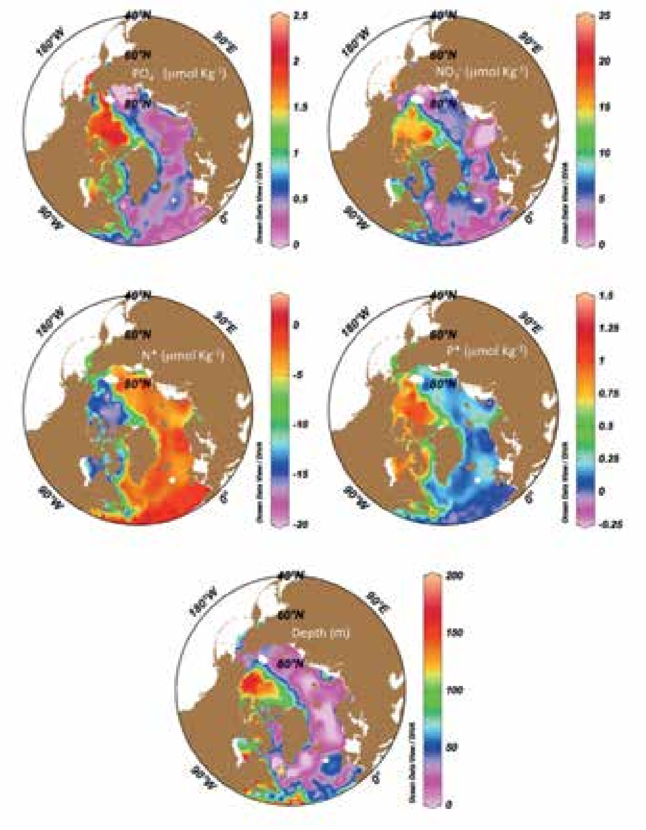

Figure 5. Horizontal distributions of phosphate, nitrate, N, and P* along the 26.6 kg m^{-3} potential density surface in the Arctic Ocean and the subarctic Atlantic. From Tremblay et al. (2015). © 2015 Published by Elsevier Ltd.*

balanced by ammonification. We evaluate that non-conservative excesses of NO_3^- in melted ice samples are due to the release of internal pools caused by handling, but find no evidence of NO_3^- accumulation in situ, where NO_3^- supply from the water column is required to support the high NO_3- assimilation rates observed during incubations. Nitrification and N_2 fixation were detectable, but represented a negligible proportion of NO_3^- assimilation. None of the variable measured could explain the variability in N_2 fixation. Ammonification explained most of the variability in nitrification across the survey area, but the latter does not appear to scale with productivity across the Arctic and seems to play a minor role in contrast to Antarctic sea ice.

Seasonal variations of phytoplankton dynamics in Nunatsiavut fjords (Labrador, Canada) and their relationships with environmental conditions (NI: M. Gosselin, Y. Gratton, M. Poulin, J-É. Tremblay, HPQ: A.G. Simo-Matchim, M. Blais). Contribution to DiveArc.

Phytoplankton dynamics and its environmental control in four Labrador fjords (Nachvak, Saglek, Okak, and Anaktalak) were assessed during summer, early fall and late fall. We observed a marked seasonal variability, with significant differences in phytoplankton structure and function between summer and fall. The highest values of PP (1730 mg C m^{-2} d^{-1}) and chl a biomass (96 mg m^{-2}) were measured during the summer bloom (Figure 7a, d). During this period, the community was composed of a mixed assemblage of diatoms and flagellates and nanophytoplankton (2–20 µm) contributed to a large proportion of the total phytoplankton abundance (25-70%; Figure 8a, d). In contrast, fall was characterized by low PP (5-350 mg C m^{-2} d^{-1}) and chl *a* biomass (5-80 mg m^{-2}) (Figure 7b, c, e, f). The fall community was largely dominated by flagellates with picophytoplankton (<2 µm) making up 70-90% of the total cell abundance (Figure 8b, c, e, f). Using the empirical relationship of Tremblay et al. (1997), which is based on phytoplankton size structure, we estimated that about the third of total primary production was potentially exported out of the euphotic zone during the three sampling periods (Figure 7g-i).

Trophic structure and resilience of benthic food webs in the Canadian Arctic and Chukchi Sea (NI: P. Archambault, C. Nozais; HQP: N. Friscourt). Contribution to DiveArc.

The objective of this project is to characterize benthic food web structure in the Canadian Arctic and the Chukchi Sea using stable isotopes (^{13}C and ^{15}N) and the sea ice biomarker IP25. Stable isotopes and IP25 data have been acquired and allowed us to define trophic redundancy, trophic separation, and community niche space. The mean isotopic composition in δ^{15}N and δ^{13}C of the surface sediments in the Chukchi Sea,

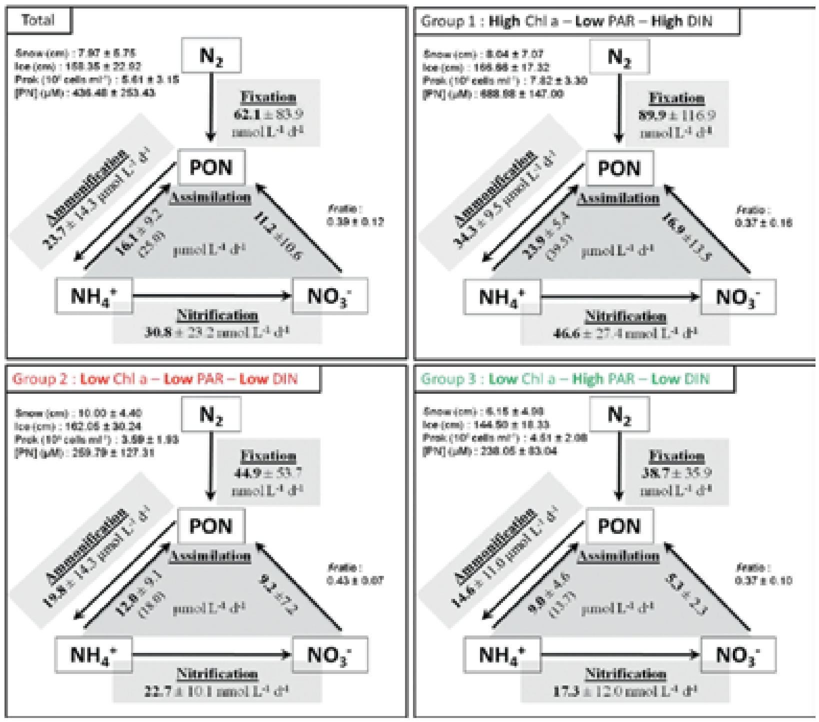

Figure 6. Schematic representation of the N cycle for each cluster group showing the mean rate for all N fluxes. General environmental conditions are given in upper left corner and the mean f-ratio on the right of each panel. Values in parentheses represent ammonium uptake rate (ρNH_4^+) corrected for possible underestimation of prokaryotes contribution.

Beaufort Sea, Amundsen Gulf, Canadian Archipelago and North Water are presented in Figure 9. Dashed lines are used to define the origin of the organic matter. The organic matter in Beaufort Sea and Amundsen Gulf seems to be from a mixed terrestrial and marine origin whereas it is from a more marine origin in the other regions.

DISCUSSION

1. The changes in biomass observed in Baffin Bay were also detected from space by remote sensing. Previous results from Bélanger et al. (2013) showed a decline in total annual PP of the North Water polynya from 1998 to 2010. Positive trends in PP in May and negative trends for the rest of the summer season also suggest a change in the phytoplankton phenology. In addition, earlier phytoplankton blooms (~ 3 weeks), as revealed by satellites, may cause mismatch between primary producers and higher trophic levels (Edwards and Richardson 2004).
2. Time-lapse images of the Eclipse Sound ice break-up give very useful information about ice dynamics, on which the entire marine ecosystem depends. Preliminary results were presented at the ArcticNet ASM (Dumont et al. 2015), during which community members of Pond Inlet demonstrated interest in this project, which will continue and expand in 2016. Results will also be used for comparison with model simulations.
3. N supply by major Arctic rivers is locally important (not shown), but does not appear to sustain a major portion of overall pan-Arctic NPP so far. Widespread N deficiency in surface

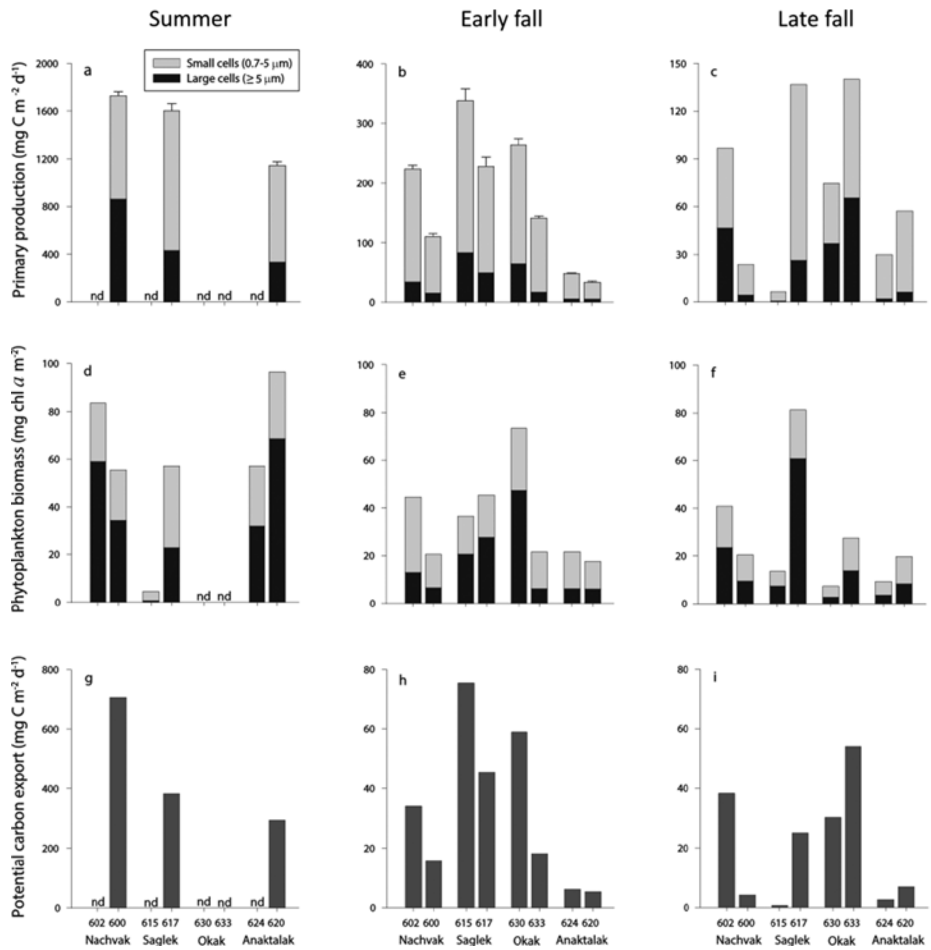

Figure 7. Variations in (a-c) primary production, (d-f) phytoplankton chlorophyll a biomass, and (g-i) potential carbon export out of the euphotic zone in Labrador fjords (Nachvak, Saglek, Okak, and Anaktalak) during (a, d, g) summer, (b, e, h) early fall, and (c, f, i) late fall. Production and biomass of small (0.7–5 µm) and large (>5 µm) cells were integrated from the surface to 0.2% of surface irradiance. In (a) and (b), vertical lines represent the standard deviation of the estimated rates. nd means no data available. From Simo-Matchim et al. (2016).

waters fosters the occurrence and seasonal persistence of subsurface layers of maximum chlorophyll *a* (SCM) and phytoplankton carbon biomass in the Canadian Arctic. The overall impacts of these layers on biogeochemical fluxes remain to be quantified directly, both regionally and at the pan-Arctic scale.

4. Given the current transition toward a predominantly seasonal ice cover in the Arctic Ocean, detailed assessments of the role of first-year sea ice in biogeochemical cycling are needed to inform ecosystem models and constrain future scenarios. With the recent work of Baer et al. (2015), our work is among the first to report direct, simultaneous measurements of N assimilation and recycling in landfast ice. The novel contributions of our work include measurements of N_2 fixation rates, an assessment of spatial variability in different N cycling steps and an analysis of how this variability relates to environmental variables on ice-covered Arctic shelves. The low N fixation rates observed in sea ice indicate that this process would not be able to compensate for the strong denitrification

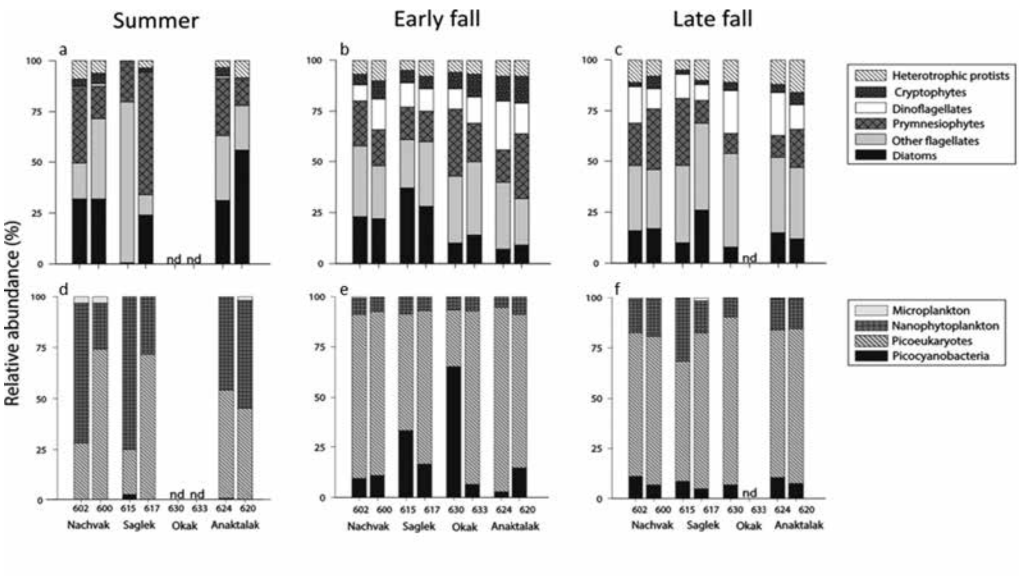

Figure 8. Variations in the relative abundance of (a-c) six protist groups (diatoms, dinoflagellates, prymnesiophytes, cryptophytes, other flagellates, and heterotrophic protists), and of (d-f) picocyanobacteria (< 2 µm), photosynthetic picoeukaryotes (< 2 µm), nanophytoplankton (2–20 µm), and microplankton (>20 µm) at the subsurface chlorophyll maximum (SCM) depth (or at 15% surface irradiance when SCM was not present) in Labrador fjords (Nachvak, Saglek, Okak, and Anaktalak) during (a, d) summer, (b, e) early fall, and (c, f) late fall. Other flagellates comprise chlorophytes, chrysophytes, dictyochophytes, euglenophytes, prasinophytes, raphidophytes, and unidentified flagellates. Heterotrophic protists include choanoflagellates, ciliates, and other heterotrophic cells. nd means no data available. Modified from Simo-Matchim et al. (2016).

taking place in sediments (Tremblay et al. 2015). The currently low levels of biological productivity observed in Canadian waters are not due primarily to a lack of light caused by the presence of sea ice, but mostly by a shortage of NO_3^- in surface waters. In this context, it is unlikely that further reduction in the extent, thickness and seasonal persistence of sea ice will lead to a large upward shift in productivity. Our review of nutrient dynamics (Tremblay et al. 2015) implies that substantial alterations of N cycling in remote source waters or a change in the extent of local vertical mixing will be required to drive enhanced productivity.

5. The summertime phytoplankton production and biomass in Nunatsiavut fjords fell in the range of other highly productive fjords, such as the Gullmar Fjord in Sweden (Lindahl et al. 1998) and the Godthåbsfjord in SW Greenland (Juul-Pedersen et al. 2015). The low value of carbon potentially exported out of the euphotic zone throughout the study (≤ 31% of total PP) suggests that phytoplankton production was mainly grazed by microzooplankton rather than being exported to greater depths. This important energy transfer towards higher trophic levels is likely responsible of the high occurrence of whales and other marine mammals in this region. Seasonal variations in phytoplankton dynamics were mainly controlled by the strength of the vertical stratification, that limited the nutrient supply, and by the large differences in day length due to the northerly location of the Labrador fjords. Due to the stratification, NO_3^- was completely depleted and silicic acid was reduced to low concentration in the surface layer during summer and limited mostly the growth of large cells. Consequently, pico- and nanophytoplankton (< 20 µm) were consistently the most abundant cells at all stations.

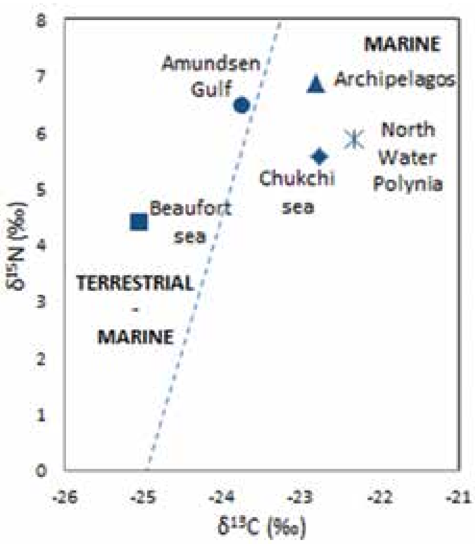

Figure 9. Mean isotopic composition of $\delta^{15}N$ and $\delta^{13}C$ of surface sediments from five Arctic regions (i.e. Chukchi Sea, Beaufort Sea, Amundsen Gulf, Canadian Archipelago and North Water). The dotted lines represent Parsons' delineating, used to define the origin of the organic matter (terrestrial-marine or marine).

Flagellates were able to dominate the fall community due to their lower light requirements than diatoms (Takahashi et al., 1978; Harrison et al., 1983). Being the first to characterize phytoplankton dynamics in Labrador fjords, our study is instrumental in assessing the response of these unique ecosystems to anthropogenic and climate changes.

6. The terrestrial and marine mixed origin of organic matter in the Beaufort Sea and the Amundsen Gulf can be explained by the fact that the plume of the Mackenzie River can expend up to the Gulf. At this point, we do not know precisely if spatial and temporal variability of benthic diversity is governed by sediment type, depth, food availability or other environmental variables. Incubation experiments were performed in the field to better understand which factors govern benthic biodiversity. The identification and enumeration of organisms and the analysis of sediments and specific compounds are carried out in home labs. Overall, the baseline data provided will enable us to make further predictions on how climate change may affect the trophic structure and resilience of benthic food webs in a changing Arctic.

CONCLUSION

Variability and change in the environment affect Arctic marine ecosystems at a variety of nested spatial scales. PP observations showed an overall annual decline with variations through the spring and summer, suggesting a change in phytoplankton phenology. In some regions of the Arctic, these changes in PP observations are thought to be linked with ice arching formation, which is a key dynamical process with profound implications on marine ecosystems. This year's report also documents the first estimates of N_2 fixation rates, spatial variability in the N cycling steps involved in assimilation and recycling and how this variability relates to a broad range of environmental conditions in landfast ice.

Finally, we report how the ongoing changes in the Arctic may affect the intensity and spatial distribution of PP and the nature of pelagic-benthic coupling. The monitoring of the Labrador fjords physical and biological properties provides a baseline to detect future changes in primary producers as highlighted in Beaufort Sea and Baffin Bay. Indeed, the phytoplankton dynamics in Labrador fjords seems mainly controlled by the vertical stratification through its impact on nitrate supply, a process that is especially sensitive to ongoing changes in the Arctic climate. We have also shown that local changes in light availability resulting from reduced sea-ice coverage and thickness is only one factor in the intricate web of local and remote drivers of PP in the Arctic Ocean. Understanding and predicting change will require an integrated biogeochemical approach that connects the small Arctic Ocean to adjacent ones and adequately resolves vertical nutrient supply processes at the regional scale.

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SECTION II. TERRESTRIAL SYSTEMS

Section II is composed of 10 ArcticNet research projects covering several biological, ecological, biogeochemical, meteorological and physical components of the Canadian Arctic terrestrial systems.

Permafrost Research for Northern Infrastructures and Improved Community Life

Project Leader

Michel Allard (Université Laval)

Network Investigators

Fabrice Calmels (Centre d'études nordiques)
Guy Doré (Université Laval)
Stephan Gruber (Carleton University)
Esther Lévesque (Université du Québec à Trois-Rivières)

Collaborators

Fiona-Geneviève Beaudoin (Transport Canada)
Bronwyn Benkert (Yukon College)
Jean-François Bergeron (Ministère des Forêts, de la Faune et des Parcs)
Jennifer Busler (MDA corp.)
Daniel Fortier (Université de Montréal)
Diane Frappier (Ministère des affaires municipales et des régions du Québec)
Duane Froese (University of Alberta)
Anick Guimond (Ministère des transports du Québec)
Sara Holzman (Nunavut Department of Environment)
Muhammad Idrees (Yukon Government)
Margaret Ireland (Jean Marie River First Nation)
Cyrielle Laurent (Geo Cardinal Services)
Anne-Marie LeBlanc (Université Laval)
Antoni Lewkowicz (University of Ottawa)
Paul Murchison (Yukon Government)
Alison Perrin (Yukon College)
Graham Strickert (University of Saskatchewan)
Heidi Swanson (University of Waterloo)

HQP

Antoine Boisson, Doctoral Student (Centre d'études nordiques)
Heather Brooks, Doctoral Student (Université Laval)
Xiangbing Kong, Doctoral Student (Université Laval)
Julie Malenfant-Lepage, Doctoral Student (Université Laval)
Mark Empey, Honours Undergraduate Student (Carleton University)
Taylor McWade, Honours Undergraduate Student (Carleton University)
Nick Brown, Masters Student (Carleton University)
Catherine Claveau-Fortin, Masters Student (Centre d'études nordiques)
Anne-Gabrielle Nolet, Masters Student (Université Laval)
Étude des mécanismes de dégradation mécanique du remblai d'une chaussée construite sur pergélisol
Christian Peart, Masters Student (Carleton University)
Joel Pumple, Masters Student (University of Alberta)
Julia Riddick, Masters Student (Carleton University)
Rupesh Subedi, Masters Student (Carleton University)
Maxime Tremblay, Masters Student (Centre d'études nordiques)

Laurent Lamarque, Post-Doctoral Fellow (Université du Québec à Trois-Rivières)
Sarah Aubé-Michaud, Research Associate (Centre d'études nordiques)
Andrée-Sylvie Carbonneau, Research Associate (Centre d'études nordiques)
José Gérin-Lajoie, Research Associate (Centre d'études nordiques)
Emmanuel L'Hérault, Research Associate (Centre d'études nordiques)
Chantal Lemieux, Research Associate (Université Laval)
Valérie Mathon-Dufour, Research Associate (Centre d'études nordiques)
Jonathan Roger, Research Associate (Université Laval)
Louis-Philippe Roy, Research Associate (Yukon College)
Denis Sarrazin, Research Associate (Centre d'études nordiques)
Hervé Gagnon, Technical Staff (Carleton University)
Ariane Bisson, Undergraduate Student (Université du Québec à Trois-Rivières)
Aaron Hill, Undergraduate Student (Carleton University)

Northern HQP

Brian Horton, Northern Research Staff (University of Manitoba)

ABSTRACT

This project is focused on supporting infrastructure maintenance and construction for the development of the Arctic and the wellbeing of communities who live on the land, while making high-level scientific contributions to permafrost science and engineering. Building on previous research results 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; and 5) to provide opportunities for the members of the research team and their students to carry out innovative research in permafrost science and engineering.

KEY MESSAGES

- Permafrost conditions and maps of potential for construction were made public for seven new communities mapped in Nunavik.
- Mapping and permafrost characterization work was also done in Yukon for the communities of Old Crow, Jean-Marie River and Ross River.
- New collaboration with architects, human and health scientists were initiated through our participation in two new SSHRC-funded major projects on habitat and communities. Those project concern mostly Northern Québec and Yukon but are of Arctic-wide significance.
- Half of the length of coastline of Nunavik was surveyed to map its sensitivity to climate change and for supporting maritime infrastructure projects.
- The team made a joint coordinated effort with the Government of Nunavut and the private sector to transfer basic knowledge and know-how in analysis and mapping permafrost for land use planning in Cape Dorset.
- The Avativut Learning package that includes the teaching software *PermaSim* is being implemented in Nunavik via the Kativik School Board and in Nunavut through the Arctic College.
- Final reports were produced for two regional hub airports in the eastern Canadian Arctic: Kuujjuaq and Iqaluit.
- A so far underestimated impact of climate change and permafrost thawing under airports is the presence of a captive water table under paved runways due to active layer deepening at greater depths than in the surrounding terrain.
- A survey of the sensitivity of the Alaska Highway to permafrost thawing was produced along its whole length in Yukon. It will be useful for the Yukon Government for setting maintenance priorities and an adapted schedule maintenance.
- A network of 40 permafrost measurement sites, comprising more than 220 individual data logging instruments, has been installed in the tundra near Lac de Gras mining area in NWT. It is designed to support model testing and to reveal surface subsidence in addition to temperature measurements.
- More than two hundred permafrost and active layer soil samples have been taken during the installation of this network and analyses of major cation and organic carbon contents are underway.
- A novel apparatus to accurately measure the freezing and thawing behaviour of soils has been designed and is currently begin built and tested.

- Terrestrial laser scanning has been investigated for quantifying local surface subsidence and methods were developed to optimize accuracy. This allows detecting ground-ice loss earlier and with more confidence; the refinement of methods for differing surface types is ongoing.
- Advanced optimization algorithms are being evaluated as a means to better constrain estimates of subsurface ice loss with model inversion and borehole temperature measurements.
- Permafrost characterization from CT-Scan image analysis shows that very ice rich permafrost may have a lower thermal conductivity than ice-poor permafrost because of gases (air mostly) trapped in bubbles.
- Temperature parameters for frost cracking that regulates ice-wedge formation and growth were more precisely measured than any time before by the use of specially design extensometers, a technology borrowed from dendrometry in forest science.
- A new analysis/decision tool is being developed for engineers and infrastructure owners to asses risks associated with climate change and permafrost thawing and eventually make financially important decisions.

OBJECTIVES

Given the above, the objectives of the project are:

1. *Permafrost mapping and measurements of thermal regime at community and project scale and along coastlines*: 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 and airfields. Periglacial coastal processes and permafrost is also studied along shorelines to help classify coastal ecosystems and provide knowledge for the construction and improvement of maritime infrastructures.
2. *Permafrost knowledge transfer and technical support to communities*: To provide support, through presentations and discussion sessions in communities, information and advice necessary to select best choices of foundations for all types of buildings. To provide informed technical support to communities for them to improve their land use planning, design their urban architecture and manage their wider lands.
3. *Development of a teaching tool for Inuit and other stakeholders*: To create and trial a teaching tool and a computer-assisted course on permafrost for widespread Inuit and public use.
4. *Support of infrastructure renovation and construction:* To work in collaboration with ministries and private sector parties involved in infrastructure renovation and construction to design better adaptation strategies, particularly for roads, airports and ports and to develop and test new engineering designs and materials for roads, airports and coastal infrastructures (e.g. convection embankments, heat drains, pre-thawing of permafrost, active and passive heat exchange systems, etc.). This objective includes the design of a risk management tool to help select the best strategies for the construction and the maintenance of roads, airports and coastal infrastructures.
5. *Development of innovative approaches and technologies:* To keep developing new methods for measurement and model-based predictions of permafrost terrain dynamics (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 measurements with new technologies is a basis for future monitoring and early warning with respect to infrastructure integrity.

Working on objectives 4 and 5 ensures that top-level scientific and engineering research is done in the project.

INTRODUCTION AND RATIONALE OF THE PROJECT

This project took over from ArcticNet's project 4.4 *Permafrost and Climate Change in Northern Coastal Canada.* For the next three years of ArcticNet, we focus the research and knowledge transfer efforts on the support of infrastructure maintenance and construction for the development of the Arctic, addressing knowledge needs both for major transportation infrastructure such as airports and highways, for mining and for housing construction and land use planning efforts in local communities. We collaborate with regional governments and encourage development of public policies to improve the quality of housing and life in northern communities. We also address how the impact of climate warming on permafrost-based ecosystems has effects on vegetation and animal resources through disturbances and ecosystem shift, with a potential cascading effect on food resources and quality of human life. By using our experience in field and laboratory research and by testing new measurement technologies for permafrost characterization we shall keep making high-level contributions to permafrost science and engineering. The composition of our team was partly renewed to allow for new ideas to be introduced, to involve expertise from Yukon for the benefit of the whole Canadian Arctic, and to address more directly engineering issues.

Therefore our project addresses permafrost related issues such as the analysis of permafrost conditions in the local and regional geological and ecological contexts, characterization of permafrost properties with proven methods and instrumentation, observing and measuring ecological changes, designing and testing innovative methods. The project also has a coastal geomorphology component in order to address some combined sea-ice and permafrost-related issues, for instance in view of potential marine infrastructure improvements, be they small facilities in communities or major installations for industrial projects.

Finally, we wish to contribute to fulfill the need for an increased number of Inuit, both young and mature, to acquire a fundamental understanding of permafrost science, particularly the basics of ground temperature regime, processes of thaw, and the major forms of ground ice found under various landforms. A better understanding of how buildings and infrastructures interact with permafrost thermal regime and ground stability is an urgent requirement for northern residents in order to improve their capacity for decision making in matters of construction, community planning and environment impact analyses over their lands. Understanding the basic principles is necessary also to maintain better practices in municipal activities such as excavations, snow removal, ditch digging and road maintenance, for instances. Knowledge and a "culture of permafrost" would provide some empowerment of residents and make them competent to elaborate projects with developers and contractors and being highly competent in matters of land development in general.

For the research team, being involved with a number of communities and infrastructure projects across the Canadian Arctic offers a great potential to sample permafrost under a variety of terrain and climate conditions, study geomorphic processes, install monitoring instrumentation and test technologies.

Working in a network of communities is a beneficial research strategy for the team.

METHODS

The team's general approach is to run permafrost projects either directly in given communities where exchanging knowledge is a continuous process, being involved in transportation infrastructure projects with government and industry or working on the land while maintaining ties with local and regional inhabitants and sharing knowledge with them. Technically, numerous research methods and technologies were used in part or in totality at the team members' research sites:

- Remote sensing by active systems (Radar and InSAR), satellite image and air photo analysis, LiDAR, GIS applications.
- Field observations of periglacial landforms and processes and study of stratigraphic sections.
- Measurement and monitoring of permafrost temperature regime across our study sites with a network of thermistor cables, the SILA network operated in cooperation with stakeholders (municipalities, departments of transport, large airports). This monitoring is done within the framework of international data sharing through Nordicana D, PDC and the Global Territorial Network-Permafrost.
- Application of geophysical methods that are appropriate for permafrost because of their general ability to discriminate between frozen and unfrozen ground and to detect masses of ice in the ground, particularly electrical resistivity and ground penetrating radar.
- Sampling in pits in the active layer, for sediments, organic matter, carbon and water contents and for describing soil profiles, using the ADAPT protocols that we helped create three years ago.
- Drilling and extracting cores of permafrost with portable drills and with specialized machinery for some large-scale projects.
- Laboratory analyses of cored permafrost samples, involving photographs, X-ray CT-Scan imaging, determination of ice structure and contents, grain-size analyses, water contents and carbon contents determination and, when appropriate, isotope analyses and radiocarbon dating.
- Laboratory determination of engineering properties of permafrost and active layer samples: liquid and plastic limits, sensitivity, thaw settlement and consolidation ratios.
- Vegetation analysis, mapping, lapse mapping and chronosequence analyses, counts of plants at various scales, dendrochronology, assessment of primary productivity.
- On selected sites, measurements of soil respiration with the help of chambers and gas analysers.
- Parameter determination and numerical modeling of thermal regime, hydrological regime, engineering applications and ecological studies.
- Consultations and exchanges of information in communities, with regional governments and infrastructure owners.

RESULTS

Permafrost mapping and measurements of thermal regime at community, project and regional scales

Nunavik

With the financial support of Québec's "Ministère des affaires municipals et de l'occupation du territoire (MAMOT)" and in collaboration with the Kativik Regional Government (KRG), a set of three maps was published for each of the following Nunavik communities: Umiujaq, Inukjuak, Ivujivik, Kangiqsujjuaq, Quaqtaq, Aupaluk, Kuujjuaq and Kangiqsualujjuaq. Each set includes a surficial geology map, a permafrost conditions map and a map of potential for construction (Carbonneau et al., 2015 a and b). An example is provided on Figure 1. The maps are considered as version 1.0. They were made by air photo and satellite image analysis and spot checked in the field with a minimum of digging and core extraction. They are however already available to the KRG, the communities and the public for the usefulness of the new spatial information they contain. Indeed they already provide an indication about the location of more solid ground and indications of areas that are not recommendable for construction. The next step will consist in better characterizing the ice contents of permafrost to fully assess sensitivity to climate change and select with a better spatial precision appropriate types of foundations for eventual construction. The drilling to extract samples for this purpose is expected to be done in the field in summer 2016, again with the requested financial support of MAMOT and with the collaboration of KRG and the communities. Geophysics, mainly Ground penetrating radar surveys at low and intermediate frequencies (50 and 100 Mhz) and Electrical resistivity surveys, are also planned to complete the drilling and, particularly,

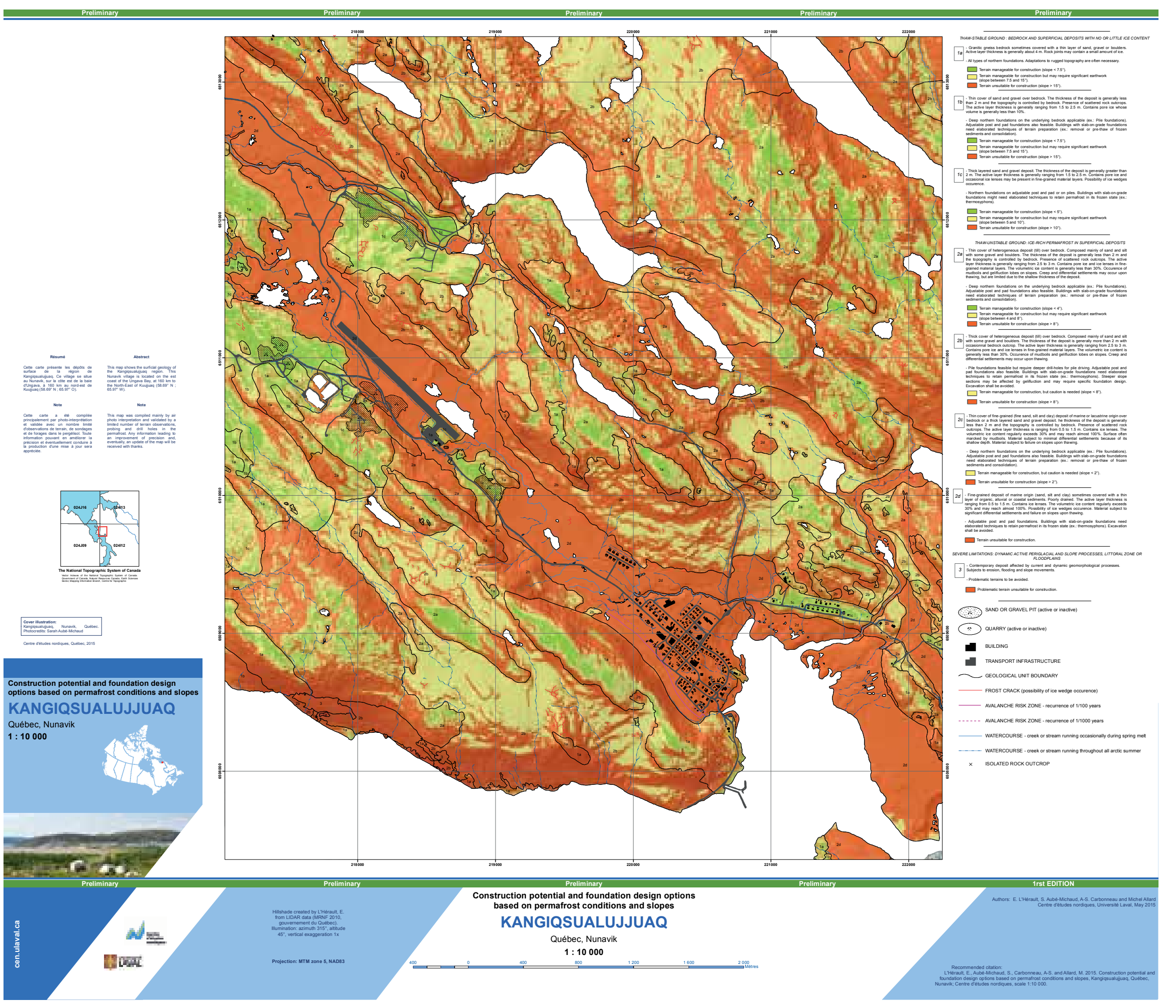

Figure 1. Construction potential and foundation design option based on permafrost conditions and slopes in the Kangiqsualujuaq region. Please contact E. L'Hérault (Emmanuel.Lherault@cen.ulaval.ca) for the original map.

to determine the depth to bedrock. This information will be highly useful as piles driven down to bedrock are more and more being considered for making stable housing foundations where it is not too deep and economically advantageous.

In the last two weeks of August a team of two research professionals, two graduate students and one undergraduate student ran geophysical surveys in Inukjuak to map bedrock depth and detect thaw sensitive permafrost layers at depth in the ground. It is becoming crucial to better characterize permafrost in that community because of its peculiar soil composition on sediments of the "Nastapoka drift Belt". The sandy silt layers in that geological formation tend to liquefy upon thawing, even at low ice contents. More geotechnical characterization is necessary and is planned for 2016. The masters' student project involved mapping and classifying all buildings of the community according to their age, foundation type, size, stability, function and owner and make analyses of their conditions relative to the type of permafrost conditions mapped. Her work was presented at the Arcticnet ASM (Claveau-Fortin and Allard, 2015).

New instrumentation to monitor infrastructure performance was installed in newly studied communities and under infrastructures that were recently upgraded for climate change adaptation. Two new thermistor cables were installed under the side of the embankment of the Quaqtaq airport runway to monitor the recovery of thawed permafrost under a re-profiled shoulder.

Nunavut

Three holes were drilled and cores extracted in the community of Cape Dorset and a thermistor cable with a supporting automated meteo station was installed. This was done in collaboration with the Government of Nunavut and provided an occasion to train local people and youngsters in the basics of permafrost, ground temperature regime, scientific instrumentation and computer applications.

Northwest Territories

Collaboration of NI S. Gruber with the Northwest Territories Geological Survey in "The Slave Province Surficial Materials and Permafrost Study" funded by the Canadian Northern Economic Development Agency and industry partners provided a unique opportunity for the installation of a unique permafrost measurement network in a region with very little alternative data. It provided a high number of permafrost and active layer samples and allowed deploying students in the field to apply newly developed methods and procedures (Figure 2).

The Slave Province Surficial Materials and Permafrost Study lead by the Northwest Territories Geological Survey drilled a large number of boreholes with depths from 1 to 20 m in the area of Lac de Gras, NWT. Around 40 of these have been installed with thermistor cables and soil samples were taken for laboratory analyses. This network of sites has been designed to reveal the variability of permafrost and ground thermal conditions on distances of meters to tens of kilometers in this tundra landscape. This is important because variability is expected to be considerable and, as a consequence, single measurement sites will not suffice to characterize a landscape and its changes. In the context of evaluating

Figure 2. Students in the field to apply methods and procedures to retreive permafrost samples.

computer simulations of permafrost conditions, the dedicated sampling of terrain variability is important to support reliable results.

At each instrumented borehole, four additional near-surface temperature data loggers have been deployed to investigate lateral variability of temperatures in response to vegetation and ground conditions. This is important because those conditions often vary on scales of several meters and thus, the true drivers of temperatures measured at depth may not be revealed with one shallow measurement. Additionally, two soil pits were dug to describe soil profiles and to obtain single-point-in-time evidence for soil moisture and soil thermo-physical properties. Surface conditions and vegetation were described based on a system of $1m^2$ subplots within $225m^2$ plots. The ongoing Masters theses of Julia Riddick (near-surface temperature variation) and Rupesh Subedi (active layer and permafrost geochemistry) are strongly based on these observations. Borehole records show that ice-rich material frequently occurs in the area.

During this field work in the Lac de Gras region, a number of peculiar surface features resembling inactive slumps and displaying a concave rim parallel to the upper edge have been noticed. The features occur in hummocky moraine and are well visible in hillshade images of high-resolution digital elevation models. Their investigation based on morphometry is the focus of the Honours thesis of Taylor McWade and collaboration with researchers at the Geological Survey of Canada. This is motivated by the working hypothesis that these features are indicative of ice-rich terrain.

Northern Yukon

Hazard mapping took place within and in the vicinity of the community of Old crow. A meteo station was installed in an undisturbed area to allow for long-term permafrost and climate monitoring of the area. A station monitoring permafrost temperature also has been installed under the pad of a new housing subdivision. It will help to monitor and assess the impact of the subdivision on permafrost. The meteo station improves the climate and permafrost monitoring network in an area where no coverage existed before.

We completed a permafrost vulnerability assessment in Ross River. The project focuses on a cluster of buildings including the school, the arena and recreation centre, the community centre, and the swimming pool. Two permafrost monitoring stations have been implemented: one in a compound, and a second under the pool. ERT surveys were run in the area and at the new sewage lagoon site to assess permafrost conditions. The project aims to develop a better site management strategy in regard on permafrost-related risk.

A Northern Contaminant Project (NCP) in the Northwest Territories

In the context of a Northern Contaminant Community Project, permafrost is being evaluated as the potential source of mercury contamination of several lakes and the fish, of Jean Marie River First Nation’s traditional territory, NWT. Permafrost cores were extracted and analysed for total mercury contents. Results showed a noticeable amount of mercury in thawing permafrost from frozen peat bogs. This project aims to better understand how thawing permafrost may impact food security of aboriginal populations.

Nunavik Coastal survey

In collaboration with the Québec “Ministère de la forêt de la faune et des parcs” (MFFP) and Environment Canada, the first half of a complete video survey of the coastline of Nunavik was done in August 2015. The survey extended from Kuujjuarapik along the Hudson Bay shoreline, up around the norther tip of Nunavik in Ivujivik, and east to Deception Bay where two nickel mines have their maritime facilities (Raglan and Nunavik Nickel (Figure 3, a and b). This project addresses the recommendation of IRIS 4 to gain better knowledge of the coastal ecosystems of Nunavik.

The procedure of coastal classification into segments and assessing their sensitivity to changes in sea ice conditions and wave climate is currently in progress. Permafrost aggradation in emerging sediments and the outer limit of shoreline permafrost along this emergent coastline are considered in the dynamic processes. One aim of the project is also to support marine infrastructure development at all scales, from community docking facilities to industrial ports. Another issue along that coastline is the conservation of rich ecosystems at the land/sea interface that have high significance for the Inuit; for instance the surveyed coastline last summer covers Kovik Bay and the mouth of Kovik River, a historical resource area for Arctic Char that is being considered for preservation by the three partnering communities of Akulivik, Ivujivik and Salluit.

Continuing data gathering and monitoring the impacts of climate change

Automated meteorological stations and thermistor cables were maintained at all the sites and communities where we have been expanding our network over the past 15 years. In Nunavik this includes all the communities and airports. In Nunavut this includes Pangnirtung, Iqaluit, Arviat and Bylot Island. Data were downloaded; they are currently being quality checked. Both the metadata and the data themselves are published online via NordicanaD and thus prodived to the Polar Data Catalogue. Like all other users, we use them ourselves in support of our work of permafrost characterization and modelling for community land planning and infrastructure adaptations to climate change. Co-funding for climate and permafrost monitoring in Nunavik was secured

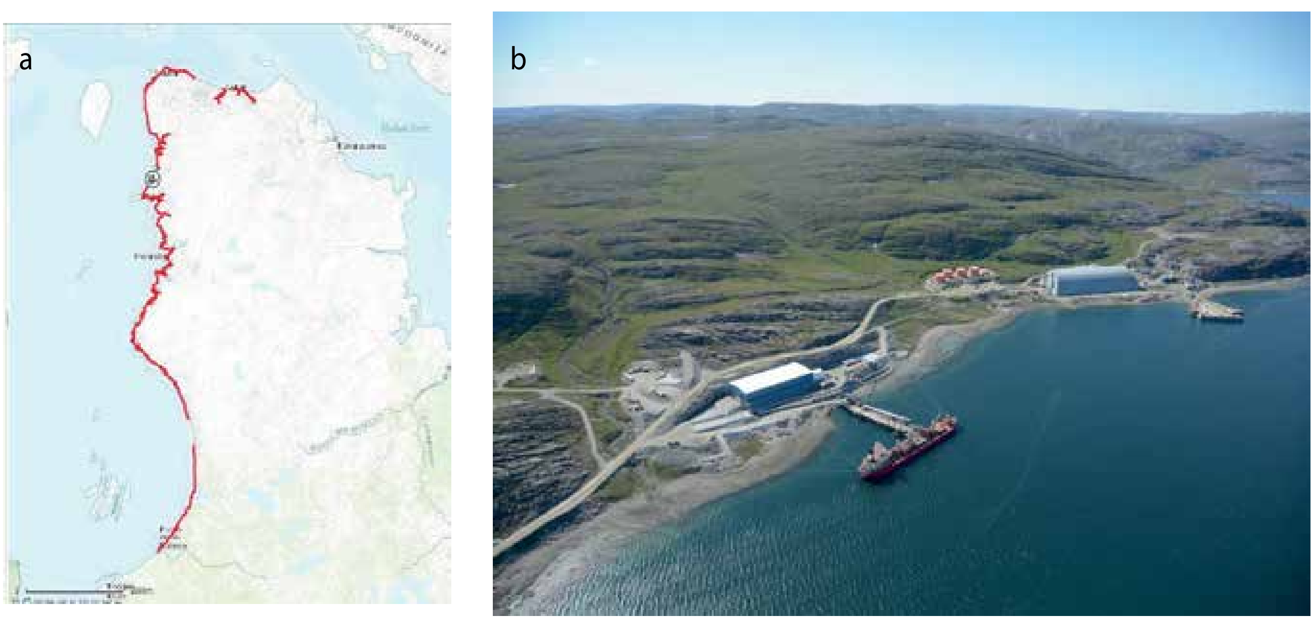

Figure 3. First half of a complete video survey of the coastline of Nunavik (a) and the two Deception Bay nickel mines facilities (b).

from three provincial departments (Ministère du développement durable et de la lutte aux changements climatiques (MDDELCC), Ministère des transports (MTQ) and Ministère des forêts de la faune et des parcs (MFFP)) for the next three years.

Permafrost knowledge transfer and technical support to communities

Cape Dorset

Our team responded to the request of the Climate Change Section of the Government of Nunavut's (GN) Department of Environment (DOE) to participate in community capacity building activities in Cape Dorset on 4-10 September. Team members from Laval and from Yukon Research Center (Norther climate exchange) join together in the community into a team operation of research and knowledge transfer. The GN-DOE organizes one such event in a selected community every year for multiple purposes: run local surveys and terrain analysis with community members, gather permafrost characterization data from several pits and drill holes, provide a first evaluation of permafrost-related issues in the community, plan for further more detail mapping work, install monitoring instrumentation (meteo station, a thermistor cable), train young residents and consult the community as to their land use planning expectations. Discussions focused on how infrastructure is impacted by changing permafrost and how these changes influence current and future development in the community. In addition to the drilling program that ArcticNet permafrost researchers ran, we also installed a monitoring station to measure permafrost temperatures. A site visit was done with community planners and land administrators to learn how to download data from the station (Figure 4a). These instructions have been sent to the high school science teacher, who, with his students, will help collect data. In 2015, two topics that got a lot of attention during meetings were foundations and building designs. These activities engaged community members, including the Hamlet of Cape Dorset, community planners and land administrators, the housing sector, elders and youth and a private contractor for GN. Outreach activities included meeting with the community managers and a public-oriented radio show (Figure 4b). These consultations were part of a larger GN-led project to map the suitability of land for future development in seven Nunavut communities. The overall goal of this project is to consider climate change impacts on Nunavut communities, and to develop adaptation measures that deal with these changes. The Cape Dorset surface deformations map produced by the private sector (3V Geomatics) was a central piece to stimulate discussion at these meetings, particularly as better surficial geology and permafrost characterization were

Figure 4. Field visit with community planners (a) and outreach activity (radio show) (b).

necessary to interpret it. Throughout the week-long discussions, key challenges were identified around the planning, development, construction, and maintenance of infrastructure in Cape Dorset. They included:

- High demand for housing, putting pressure on timelines for planning and construction of new infrastructure development;
- Very rocky, steep landscapes that are not suitable for development;
- Drainage issues due to disrupting natural drainage patterns;
- Current energy restraints, stopping any new development; and
- Knowledge gaps in surficial geology conditions.

These permafrost and geomorphology issues are widespread in Arctic communities.

Nunavik villages

Visits to communities in Nunavik are done in collaboration with the KRG as the regional government and the 14 communities are developing lands use plans. Given population growth, needs for infrastructure and social housing and the strong community will to modernize and improve their urban environment, the scope of that task is large and indeed is targeting the urbanization of the communities by themselves. The team from CEN was present for presentations, discussion, and knowledge exchange in April (18-24) in Ivujivik, Inukjuak and Umiujaq. Quaqtaq and Kangiqsualujuuaq were visited from 24 May to 7 June, with a working stop in Kuujjuaq. Inukjuak was visited again from 19-28 August. Work by masters student Catherine Claveau-Fortin in Inukjuak gave way to a paper on the project published in Nunatsiaq News, following her poster presentation at the annual ASM in Vancouver (Figure 5) (Nunatsiaq News, January 28, 2016).

The schedule for making community land uses and development plans is planned by KRG and the communities (3-4 communities per year). Our team will accompany KRG in all communities over the 3-4 years period the process will continue.

Setting standards for geotechnical investigations and construction

Network investigators M. Allard (Laval University) and F. Calmels (NCE, Yukon College), and research professional E. L'Hérault serve as expert members on the new standard setting committee *"Geotechnical Site Investigations for Building Foundations in Permafrost Zones"*. Those published standards are intended particularly for consulting engineers who undertake mandates for doing geotechnical site investigations prior to construction in communities. Methodologies developed over the recent years by our ArcticNet team such as drilling with portable drills and the sequencing

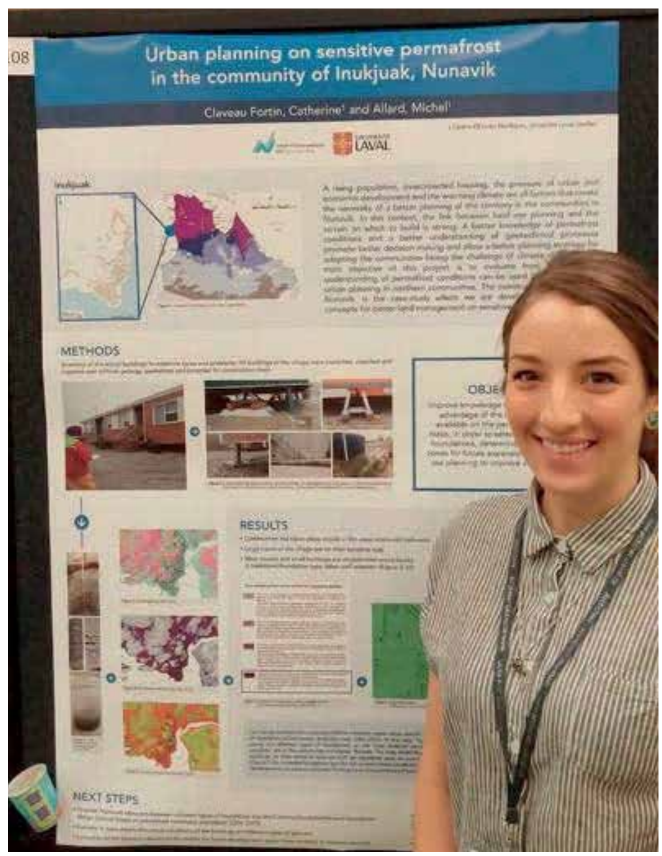

Figure 5. Masters student Catherine Claveau-Fortin presenting a poster at the annual ASM in Vancouver.

of geotechnical sample analyses are expected to become included in the Standards of practice. Similarly, Mr. L'Hérault is completing a *"Guide for foundations design for small buildings on permafrost"* on behalf of the "Société d'Habitation du Québec"; Pl. Allard authored the two first chapters of the guide.

Publication in the science and engineering community

Finally, our general methodology for producing permafrost maps for community planning and construction was published as a proceedings paper of the joint 68th Canadian geotechnical Conference/7th Canadian Permafrost Conference in September 2015 (Carbonneau et al., 2015).

Development of a teaching tool for Inuit and other stakeholders

Permafrost LES in Avativut-Nunavik

This part of our project is referred to as a Learning and Evaluation Situation (LES), the terminology used by the Kativik School Board for specialized training curriculum on given matters of interest. This curriculum for the LES was finalized in 2015 (Figure 6a). The Kativik School Board (KSB) has adapted and translated it, for both secondary 1st and 2nd cycle students. The educational activities are being implemented during winter 2016. The LES lessons (a package of 10 lessons) cover matters ranging from the basic principles of permafrost thermal regime to ground ice types and landforms and finally to collating an original glossary of applicable Inuktitut terms with the help of elders.

The methods taught in the package include analysis of photographs, reading of surficial geology maps, ground temperature measurements, graphing data and using a tutorial in computer simulations; this permafrost thermal regime simulator, *PermaSim,* is a key teaching tool in the LES (Figure 6b). We completed the development of this interactive educational software. This software allows the student/user to view changes to the ground thermal regime over a one-year period using real local climate data in communities of Nunavik with realistic soil and surface parameters (soil types, vegetation types, variable snow cover thickness). Video tutorials and User Manuals, both in English and French, have been produced. The software is actually compatible with a PC platform. An application will be developed in the next year with the UQTR Computer Science Department for the use of *PermaSim* on iPads as KSB has invested to provide these tools in the Nunavik classes.

Feedbacks of trials from schools will be analyzed during winter 2016 and interactive and graphic outreach products will be designed to better engage the students with the results and the process of collecting scientific data. These products will be distributed in all Nunavik schools before the end of March.

The Avativut Mobile Teacher Training Workshop has been developed and training sessions have been organized in two communities: Salluit on November 3rd and Kangiqsujuaq on November 5th 2015. Two other training sessions are planned for February in Umiujaq and Inukjuak. These sessions should make the teachers more aware of the nature of the Avativut Program and the importance of collecting and registering their data for the building of a long term environmental database. Inuit Culture and Inuktitut teachers are encouraged to participate in the training sessions to promote a better cultural collaboration between southern science teachers and Inuit teachers. The involvement of Inuit teachers will greatly contribute to the sustainability and relevance of the Avativut Program. KSB representatives attended the Kangiqsujuaq workshop and interesting discussions occurred involving all parties (science teachers, Inuit teachers, KSB curriculum developers, researchers and Inuit commissioners).

Avativut in Nunavut

Avativut and the permafrost LES are also being implemented in Nunavut through the Environmental

Technology Program of the Arctic College: J. Gérin-Lajoie met with Environmental Technology Program (ETP) students in Iqaluit on November 27th (Figure 6c). She presented the results from data collected by students for seven years (2009-2015). Students have taken measurements on berry productivity, soil surface temperature, plant cover within and outside open top chambers acting as warming experiments. She also presented the permafrost LES material, including the Landform Powerpoint, surficial geology maps and ancient aerial photographs. *PermaSim* basic features were also introduced to the students. A hands-on workshop will be organized in the future to experiment *PermaSim's* full potential with the students and their teachers. As in Nunavik, local climate data (i.e. community specific) are used in Nunavut to drive the simulator; the students and administrators thus can calculate active layer depth and permafrost temperature regime in their own community and compare with thermistor data. PermaSim is therefore also a freely available tool for managers and engineers that need to carry geotechnical analyses for construction project in communities.

The permafrost educational material, including *PermaSim*, has been designed to empower the Inuit Youth with a basic permafrost culture in the perspective of them being the future leaders and making knowledge-based decisions on permafrost issues. As this material is embedded in the KSB

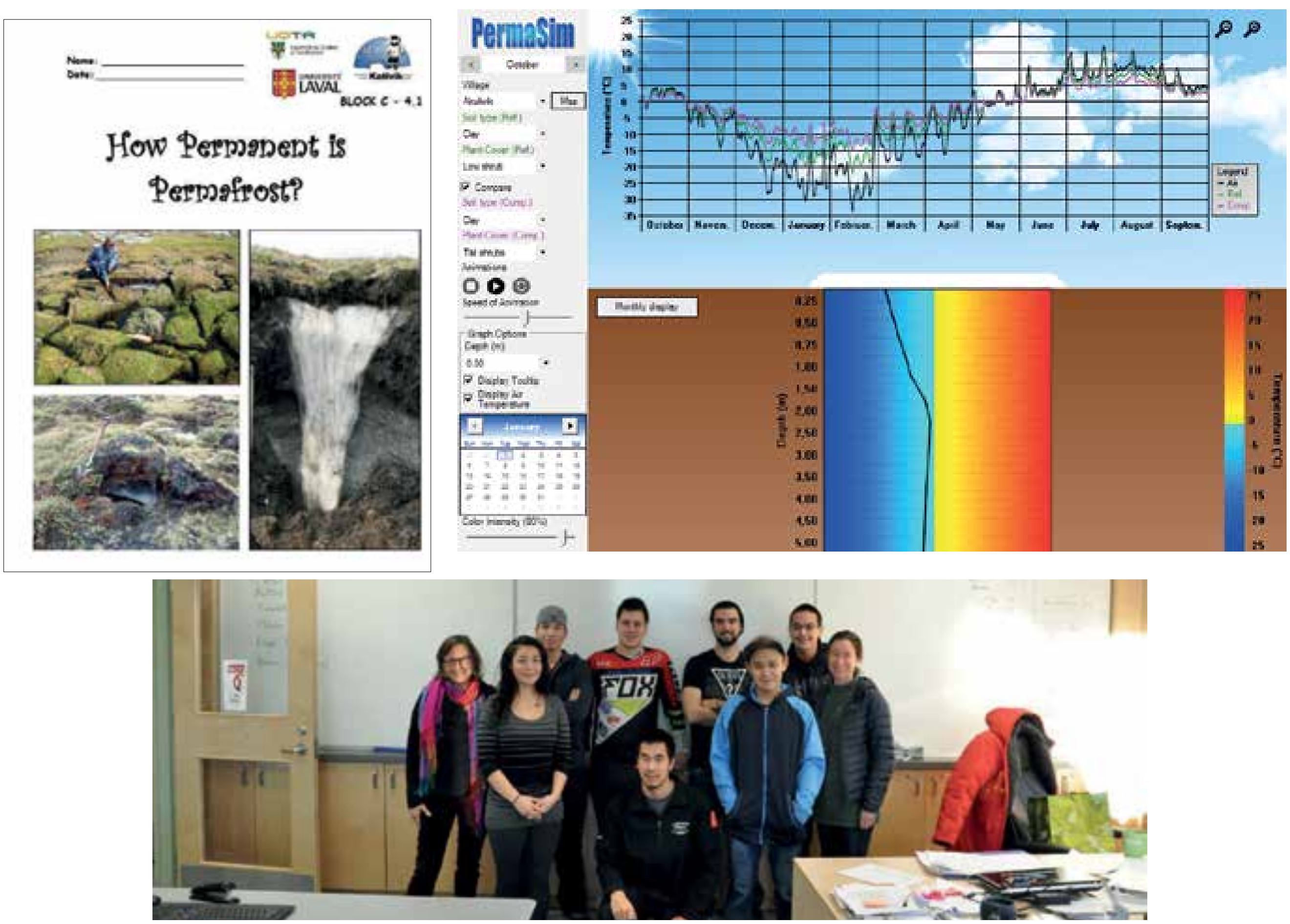

Figure 6. Learning and Evaluation Situation (LES) in Avativut (a) and a screan capture of the permafrost thermal regime simulator, PermaSim (b) and Environmental Technology Program (ETP) students in Iqaluit (c).

Science and Technology curriculum across all Nunavik secondary schools, we can assume that it will reach the largest possible Youth audience.

Knowledge transfer needs to be done in both ways, between western science and traditional and local knowledge, so both knowledge systems enrich each other. As an example, the participation of Inuit elders in the Avativut Program activities is encouraging multi-directional exchanges between teachers, students, local experts and researchers. Working with Inuit collaborators and hiring Inuit field assistants are also good ways to promote knowledge transfer at a personal level. Finally, the compilation of a glossary of terms applicable to permafrost in Inuktitut shall help the expansion of the "permafrost culture" in the Arctic.

Support of infrastructure renovation and construction

Iqaluit and Kuujjuaq airports

The team has completed research on two major airports of the Eastern Canadian Arctic: Iqaluit and Kuujjuaq. The final Iqaluit airport report was transmitted to the Government of Nunavut, Transport Canada and Arctic Infrastructure Partners (AIP) on December 17th after four years of integrated geological, climatological, geophysical and engineering research (Mathon-Dufour and Allard, 2015). The airport is built over a sandur-delta sandy plain that overlies in large part fine-grained, saline, marine sediments. Average permafrost temperature (15 m deep) is –5 °C. A network of large ice wedges extend under the runway, the taxiways and the aprons. In warmer summers their top thaws with the deeper active layer, creating linear depressions and damaging paved surfaces. As the thaw penetration rate is faster and thaw depth are larger under the paved surface than on the unpaved sides due to the albedo effect, a perched water table saturates is captured in the active layer beneath the runway. This high water content delays freeze-back because of the latent heat effect and also generates some drainage problems under the paved embankment. Adapted drainage works (french drains) had to be designed and installed in conjunction with new ditches. The stability of the infrastructure surface will remain sensitive to further climate warming and, particularly, to warmer than normal summers. Therefore the risk to the runway surface operational capacity associated with fast climate warming or exceptional warm summers is a concern for the coming years. Close collaboration was maintained with AIP and its partnering contractors for providing the necessary permafrost data and mathematical models for repairing and insulating a large number of frost cracks and ice wedge troughs in the runway, setting a new taxiway to replace the failing taxiway A and planning for a monitoring of performance for the coming years of operation. Figure 7 provides a comprehensive (executive) view of the various sectors of the infrastructure with the dominant permafrost issues.

Kuujjuaq airport in Nunavik has a very different situation. It was initially built in the 1940s (by the US army in the same time as Iqaluit) on poorly drained, gently sloping, terrain where some fens were present. Following the important warming (by about 3 °C) that took place since the mid-1990s, the active layer is already thick enough beneath the runway for the infrastructure to behave practically as in a non-permafrost area. Deeper than the permafrost table at 3 m, the temperature of the permafrost is close to 0 °C (-0.65 °C) and the soil consists mostly of ice-poor compact till and of gravelly sand. There is practically no risk anymore that permafrost thaw will generate deformations of the runway. However, just like in Iqaluit the thaw front progresses faster under the paved surface than under the sides, therefore retaining a captive water table.

Both runways are also subject to frost cracking in winter which opens infiltration paths through the pavement for meltwater and precipitation water, further adding to the water table captive water tables and groundwater movement under paved runways now appear as a so far unexpected impact of climate warming in addition to thaw settlement where there is excess ground ice. When the water table is close to the surface beneath the pavement, the surface may lose bearing capacity and is subject to deformations such as rutting under the load of heavy aircrafts and efforts need to be made to drain it as much as possible (Figure 8).

Other airports in Nunavik

In 2015 we monitored adaptation measures that were implemented since 2012 at various airports and access roads in Nunavik as a scientific support to Ministère des Transports du Québec (MTQ). Those measures had been decided upon our previous characterization work of the late 2000s. The modified airports are Salluit (truncated gentle slope side of embankment), the Salluit access road (heat drain embankment monitored with fiber optics distributed temperature sensing), Quaqtaq (truncated slope + new ditch system), Tasiujaq (various embankment sides) and Puvirnituq (air convection berm).

A specific new permafrost characterization study was made for the 6 km long access road from the community of Tasiujaq to the local airport.

Alaska Highway in Yukon

For a fourth year, a permafrost vulnerability assessment survey is taking place along the northern section of the Alaska Hwy, YT. The objective of 2015-2016 study is to identify and characterize candidate sections to implement adaptation techniques. Six sites have been investigated using permafrost drilling, ground temperature monitoring and Electrical Resistivity Tomography (ERT). Four sites have been retained, and the adaptation methodology is currently under development. Implementation is scheduled for 2017-2018. This project is a collaboration between two NIs, F. Calmels and G. Doré, and involves one Ph.D. student, Xiangbing Kong.

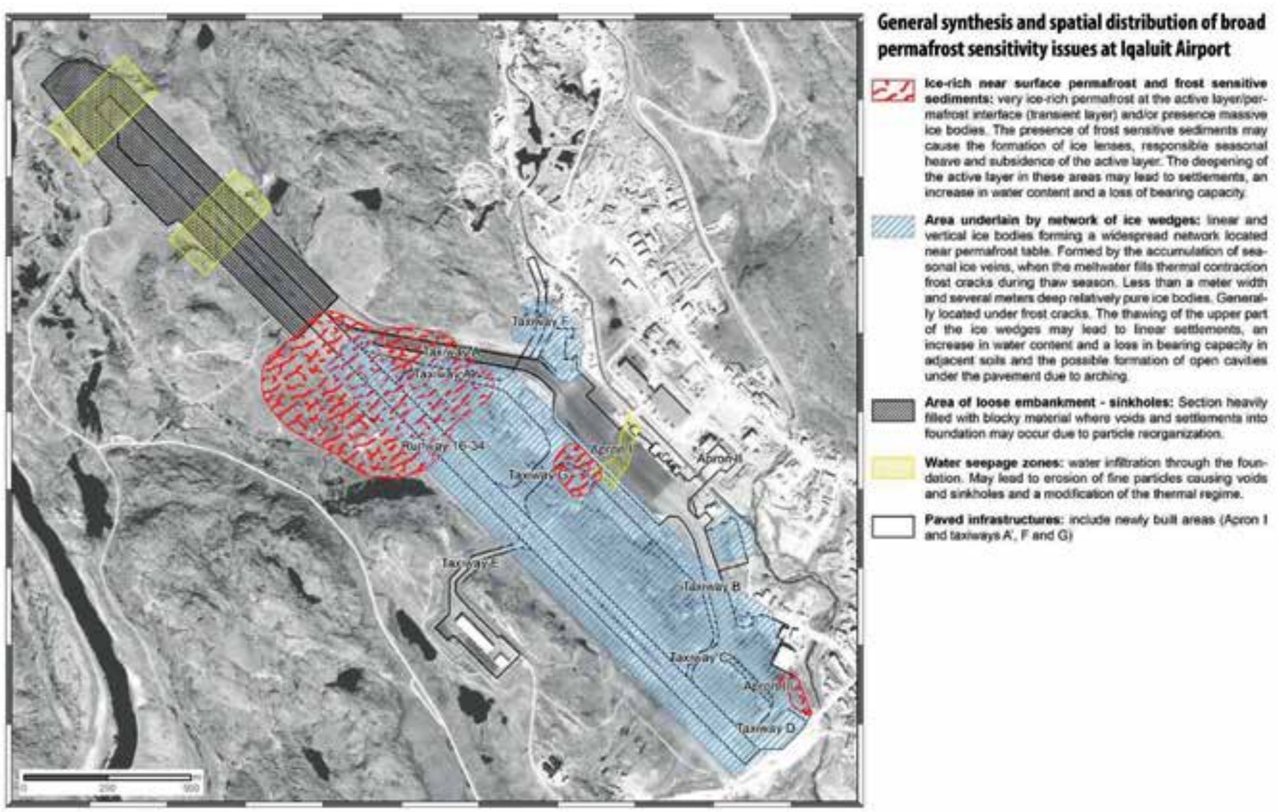

Figure 7. Example of the various sectors of the airstripe infrastructure with the dominant permafrost issues at the Iqaluit airport.

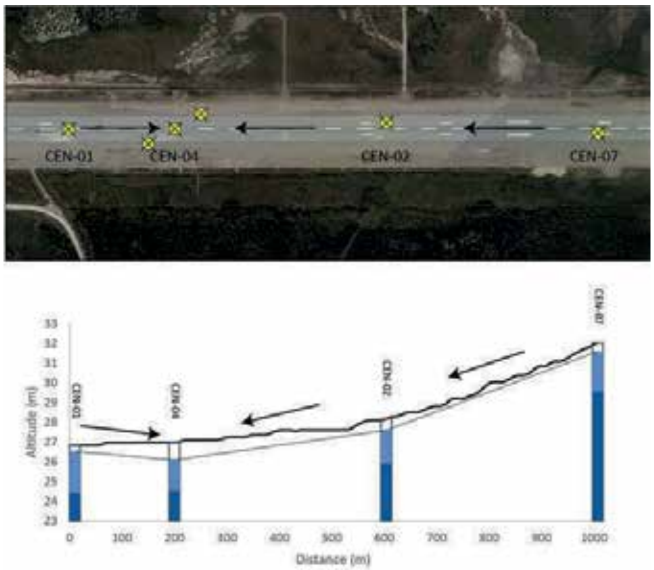

Figure 8. Water level (clear blue) and permafrost table (dark blue) in wells at the Kuujjuaq airport. Black arrows indicate the water flow direction.

Development of innovative approaches and technologies

Determination of thermal conductivity by CT-Scan measurememts

CT-scan quantitative image analysis for determining permafrost physical properties was further developed. The procedure works on undisturbed permafrost samples that are cored in the field and brought back to Laval in the frozen state. Visible ground ice contents (in pores ≥ 200 μm in size, the voxel resolution of the imaging system) are determined by image classification and quantification and a correction is applied for total water content that includes invisible ice below system resolution. The calculation of thermal conductivity is done by algebraic addition of the conductivities of the two components soil and ice-air mixture; one of three different models of algebraic additions is applied depending on the cryostructure orientation: horizontal (ice lenses), vertical (veins and wedges), massive (± homogenous distribution of ice in the sample). One important finding that came out through the research and development process is that very ice rich permafrost is not as conductive as ice-poor permafrost (contrary to general belief) because of the high porosity and air content (gas) of permafrost ice. The correlation between lab results and other methods as reported in the literature is excellent (Figure 9). Further improvements are planned, either by using a higher resolution scanner or by enhancing the soil/ice classification scheme of the image analysis to improve the direct measurement of the total ice content (Ducharme et al., 2015).

Measurements of ice wedge frost-cracking temperature with extensometers

Thanks to the initiative of research professional Denis Sarrazin at CEN, extensometers that were originally designed as expanding collars to make precise measurements of circular stem growth in forestry were adapted and installed across ice wedge cracks on Bylot Island as linear measurement devices to measure thermal contraction and expansion (Figure 10, a and b). The data recorded with dataloggers along with temperature allowed us to make precise measurements of the timing, rate and temperature-dependance of the frost cracks. The results show that the active layer may (not always depending on surface conditions) crack first and contract by a couple of millimeters in early winter once it has frozen back. But sudden extension of the cracks by several millimeters occurs when the permafrost beneath (in the ice wedge) cracks once its temperature falls below –10 °C. Cracks in the permafrost open to the surface dilate and contract with air temperature variation over the winter. They reach maximum widths of 15-20 mm by the end of March. They close partially during springtime warming. But they remain wide enough (7-10 mm) in June when snowmelt occurs. Water then percolates in them and adds a new vein into the ice-wedge (Sarrazin and Allard, 2015).

The new technology yields for the first time physical results that are well in line with theoretical physical calculations of Lachenbruch's classical paper in 1962, contrary to previously used techniques based on the breaking of electrical wires set across cracks, they also provide useful insights on the climatic controls

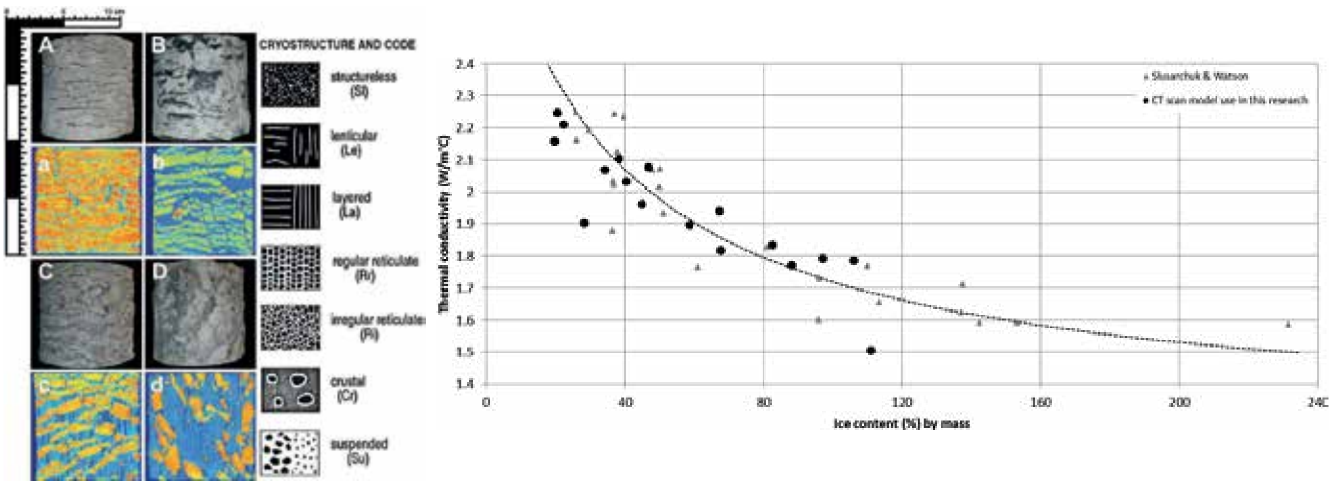

Figure 9. Permafrost core samples from CT scan images and the correlation between lab results and other methods as reported in the literature.

of the frost cracking process that is responsible for the formation of ice-wedges, infiltration of organic matter in the permafrost, and the cracking of roads and runway surfaces.

Laser scanner measurements to measure thaw settlement and ground ice loss

At Carleton University, a surveying methodology for measuring/monitoring the loss of ground ice as permafrost thaws is being developed. The tests were begun during the course of the *Slave Province Surficial Materials and Permafrost Study.* The elevation of each surveyed site has been surveyed accurately with a terrestrial laser scanner and traditional total station measurements. This is to enable the detection of ground ice loss via terrain subsidence based on repeated surveys after several years. This is important because atmospheric warming and shrub growth are likely to affect active-layer depth, and the loss of ground ice may not be detected in temperature measurements alone. The workflows and methods for scanning and surveying have been carefully designed and tested by students together with a Yellowknife-based surveying company. Multiple local benchmarks in bedrock help to maximize the repeatability of measurements. The establishment and testing of high-accuracy methods for local surveying and scanning of permafrost plots and for determining snow cover are the foci of the theses of Christian Peart (Masters) and Mark Empey (Honours). While temperature is an important and easy-to-measure quantity characterizing permafrost, ice loss is more the variable of interest. In the Master's thesis of Nick Brown, we attempt to use advanced optimization algorithms to better constrain estimates of subsurface ice loss with model inversion and borehole temperature measurements.

New method to measure permafrost unfrozen water content and derive Freezing Characteristic Curves

The freezing-characteristic curve (FCC) expresses the amount of liquid water in a porous medium such as soil or rock as a function of temperature. The liquid water content governs many of the characteristics that make permafrost change relevant, including mechanical strength, hydraulic permeability or electric/dielectric properties. While many theoretical models for the prediction of FCCs from soil characteristics exist, the measurements required for their testing and better parameterization are few. To address this, a novel apparatus to make accurate dielectric measurements on frozen soil while having precise and fast temperature control is being developed at Carleton University. Numerical simulation of the device has

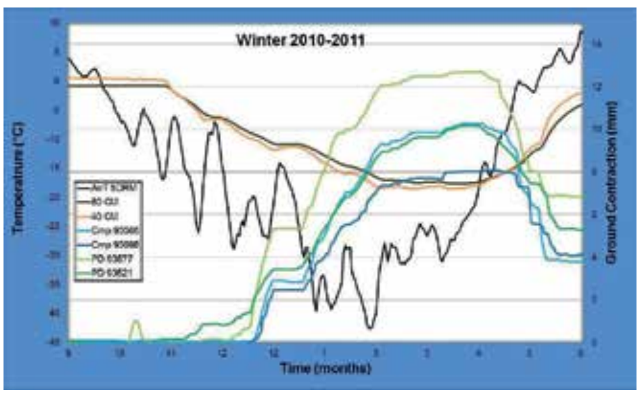

Figure 10. Device to measure thermal contraction and expansion.

shown promising results and first tests of the actual device are expected in the spring of 2016.

Risk analysis for paved infrastructures

As the climate warms in the coming years inter-annual variations in ground thermal regime and active layer thickness generate a risk that on warmer years a critical depth of thaw will be exceeded, thus affecting the stability of infrastructures. Particularly sensible infrastructures are paved airport runway surfaces that can be severely damaged by ground ice thawing. Thawing of ice-wedges beneath runways is especially a cause of linear damages (furrows, localized settlements, ultimately collapse) that affect the performance of runways and are very costly to repair.

Mrs. Heather Brooks' Ph.D research under the supervision of NI G. Doré aims at developing a quantitative risk analysis tool for transportation infrastructures and the validation of the tool developed with case studies, like the Iqaluit airport in Nunavut. The tool is based upon a tree decision-making scheme to help select the best adaptation techniques considering the local context and needs. During 2015, the project progressed from a conceptual framework, where the research on quantitative risk assessment transitioned from literature review analyses, to experimental design, probability of occurrence calculation and computer programming. The quantitative risk project will focus on six common and high consequence hazards (failure modes) presented in Figure 11. During the researcher's review of the literature for each failure mode, a lack of information on the failure processes for the mechanics of bridging or arching over ice wedges or voids was discovered. A laboratory experiment was designed to analyze this failure mode in further detail.

The other failure modes have been characterized. A failure equation is available or has been developed, and, in order to complete the probability of occurrence analysis, a computer program (in MS Excel and its developer program Visual Basic for Applications) is in development. At the end of 2015, a Monte Carlo based statistical analysis of thaw depth calculation based on Modified Berggren Equation was completed and its results, based on data from the Iqaluit Airport (collected by Valérie Mathon-Dufour under the direction of Michel Allard), were presented at the 2015 ArcticNet Scientific Meeting.

In fall 2015, research began concerning the specific objective of producing another decision-tree to help select the best adaptation techniques. This part of the research is partly financed in collaboration with NI Fabrice Calmels from the Ytukon Research Centre as part of a larger project. Field visits have been done to

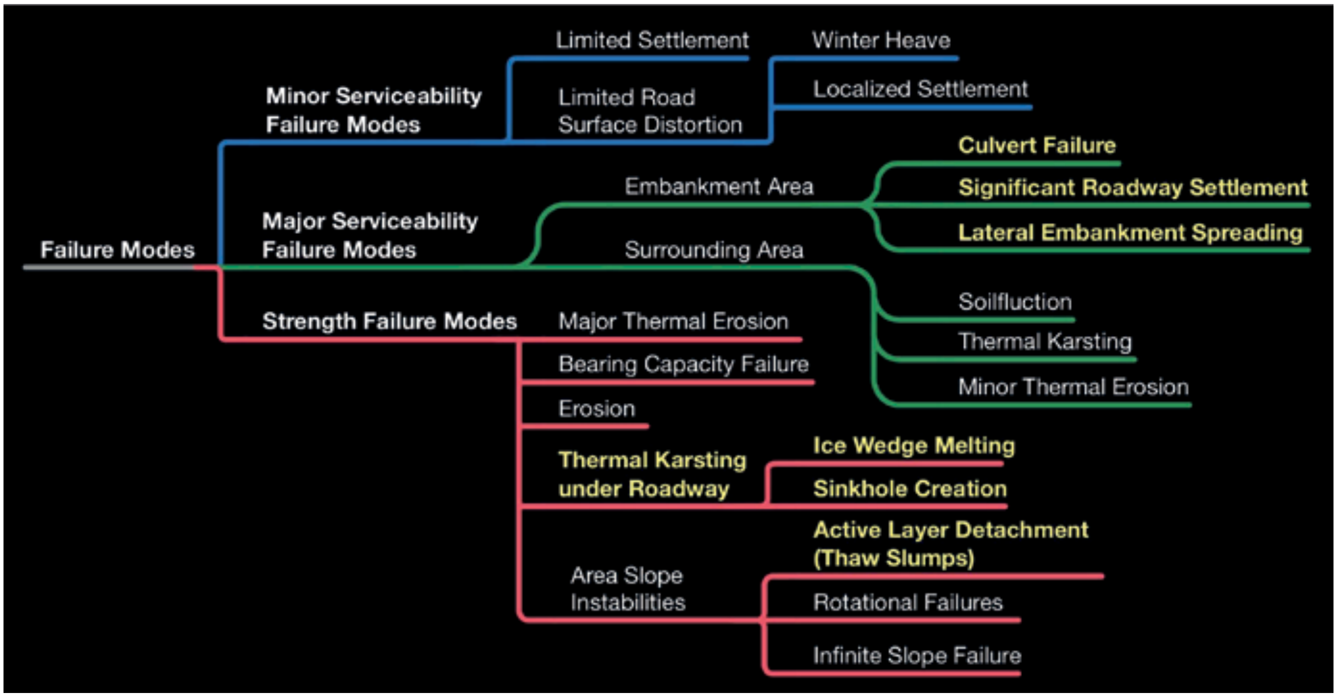

Figure 11. Schematic of quantitative risk project for six common and high consequence hazards.

select sections of the Alaska Highway (Yukon) with permafrost degradation problems. For each section, the best adaptation techniques and designs suitable for those specific sites will be produced to allow Yukon Highways and Public Works, the organization funding the project, to rebuild a more stable road in those sections. First results will be available in April 2016.

Follow-up on previous work

NIs Lévesque and Allard have continued their collaborative work on vegetation-snow cover-permafrost relationships. Masters' theses were completed. Similarly, previous work undertaken by NI Allard and former Ph.D. student M. Jolivel on the impact in coastal waters of carbon transfer from permafrost thaw and ecosystem changes east of Hudson Bay was published. Theses and papers stemming from the previous project in 2015 are reported in the list of theses and publications.

New collaborations with the human sciences and with architects/house designers

Project leader Allard is one of the co-researchers in the new project "Habiter le Nord Québécois: mobiliser, comprendre, imaginer" funded by the Partnership Grants program of SSHRC (2 046 176 $; 2015-2020). Dr. Geneviève Vachon from Université Laval's school of architecture is the project leader. Research collaboration is now in effect with architects, urban planners, land use planners, cultural geographers and health researchers (M. Riva, also ArcticNet project leader, is a co-researcher). The research team includes representatives from KRG, Makivik and Kativik Municipal Housing Bureau. We expect to bring new creative and culturally adapted approaches to both housing and urban designs in Nunavik.

NI Calmels is a co-researcher in the new project entitled "The human dimensions of a thawing landscape" funded for three years ($239,525.00; 2015-2018) under the Community and College Social

Innovation Fund of SSHRC. The project leader is Dr. Graham Strickert from Yukon College.

DISCUSSION AND CONCLUSION

In community planning more work now seems necessary to better map the depth to bedrock or to some solid underlying sediment layer in order to favor the use of anchored piles. This approach seems more urgent in Nunavik where ground temperatures are warmer and will get to the thawing point more rapidly. The challenge of planning and adapting will become more demanding for communities.

Innovative methodologies such are extremely useful to map permafrost sensitivity to thawing and to disturbances. Characterization tools in the field and in the laboratory are bringing more efficient and faster diagnostics upon which decision will be made. Contributions to technology, some unique so far to our group (CT-Scan, laboratory techniques, Distributed Temperature Sensing (last year's report), InSAR (idem), Laser scanning, making Freezing Characteristic Curves) are in progress and are already applied in science, in community work and in infrastructure research.

Education and training material for the Inuit is being produced are we are beginning to build up the desired "permafrost culture" into the Inuit Education System.

Project NIs are deeply involved in collaborative research with governments and the engineering community in developing new approaches to tackle the issue of construction and maintenance of infrastructure on permafrost.

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Most of all, the project would not be possible without close collaboration with a large number of Inuit of all generations in a large number of communities.

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Effects of Climate Shifts on the Canadian Arctic Wildlife: Ecosystem-Based Monitoring and Modelling

Project Leaders

Dominique Berteaux (Université du Québec à Rimouski); Gilles Gauthier (Université Laval)

Network Investigators

Joël Bêty (Université du Québec à Rimouski)
Alastair Franke (Canadian Circumpolar Institute)
Grant Gilchrist (Carleton University)
Dominique Gravel (Université du Québec à Rimouski)
Nicolas Lecomte (Université Laval)

Collaborators

Michel Allard (Université Laval)
David L. Anderson (The Peregrine Fund)
Malik Awan (Government of Nunavut)
Kurt Burnham (High Arctic Institute)
Mitch Campbell (Government of Nunavut Wildlife Management Division)
Steeve Côté (Université Laval)
Oliver Curran (Baffinland Iron Mine)
Andrew Derocher (University of Alberta)
Sébastien Descamps (Environment Canada - Canadian Wildlife Service - Northern Conservation Division)
Florent Dominé (Centre national de la recherche scientifique)
Knud Falk (Independant Contractor)
Lee Foote (University of Alberta - Department of Renewable Ressources)
Daniel Fortier (Université de Montréal)
Eva Fuglei (Norwegian Polar Institute)
Drikkus Gissing (Government of Nunavut)
Rolf Anker Ims (University of Tromso)
David Lee (Nunavut Tunngavik Incorporated)
Josée Lefebvre (Environment Canada - Canadian Wildlife Service - Quebec Region)
Pierre Legagneux (Université Laval)
Shawn J. Leroux (Memorial University of Newfoundland)
Travis Logan (Ouranos)
Oliver Love (University of Windsor)
Soren Moller (Roskilde University)
Stephan Robert (Agnico-Eagle Mines)
Niels Martin Schmidt (Aarhus University)
Mike Setterington (Government of Nunavut Wildlife Management Division)
Paul Sibley (University of Guelph)
Paul A. Smith (Carleton University)
Guillaume Szor (Université du Québec à Rimouski)
Jean-François Therrien (Université Laval)
Mélanie Veilleux-Nolin (Government of Quebec)
Nigel Gilles Yoccoz (University of Tromso)

HQP

Clément Chevallier, Doctoral Student (Université du Québec à Rimouski)
Dominique Fauteux, Doctoral Student (Université Laval)
Effets de la prédation sur la dynamique des populations des lemmings en milieu arctique
Loreleï Guéry, Doctoral Student (Université du Québec à Rimouski)
"Influence of climatic fluctuations on Common Eider life history and population dynamics: variation within and between populations"
Sam Iverson, Doctoral Student (Carleton University)
The emergence of avian cholera and its role in regulating northern common eider populations in the eastern Canadian Arctic
Frankie Jean-Gagnon, Doctoral Student (Université du Québec à Rimouski)
Impact des conditions de la glace de mer sur la reproduction des eiders à duvet (Somateria mollissima) nichant dans l'Arctique canadien
Claire-Cécile Juhasz, Doctoral Student (Université de Moncton)
Sandra Lai, Doctoral Student (Université du Québec à Rimouski)
Écologie spatiale du renard arctique (Vulpes lagopus) à l'île Bylot, Nunavut.
Jean-François Lamarre, Doctoral Student (Université du Québec à Rimouski)
Relations trophiques indirectes, connectivité migratoire et interactions saisonnières chez les limicoles nichant dans le Haut-Arctique
Jennifer Provencher, Doctoral Student (Environment Canada - Science and Technology Branch)
The effects of multiple stressors, including contaminants and parasites, on marine birds in Arctic Canada.
Cynthia Resendiz, Doctoral Student (Université Laval)
Audrey Robillard, Doctoral Student (Université Laval)
Utilisation de l´espace et mouvements hivernaux chez un prédateur de la toundra, le Harfang des neiges
Justin Roy, Doctoral Student (Université du Québec à Rimouski)
Travis White, Doctoral Student (Carleton University)
Lyndsay Gauvin, Honours Undergraduate Student (Université de Moncton)
Andréanne Beardsell, Masters Student (Université Laval)
Nik Clyde, Masters Student (Carleton University)
Marine Nutrient Subsidies To The Terrestrial Environment Of Common Eider Nesting Islands In The Canadian Arctic
Nicolas Coallier, Masters Student (Université Laval)
Validation croisée des méthodes d'estimation d'abondance des lemmings et évaluation de leur précision dans l'Arctique canadien
Philippe Galipeau, Masters Student (Université du Québec à Rimouski)
Utilisation de l'habitat, ségrégation spatiale et impact du développement industriel minier durant la reproduction chez quatre espèces de rapaces nichant dans le Haut-Arctique canadien
Kevin Hawkshaw, Masters Student (University of Alberta - Department of Renewable Ressources)
Erik Hedline, Masters Student (University of Alberta - Department of Renewable Ressources)
Vincent Lamarre, Masters Student (Université du Québec à Trois-Rivières)
Effet de la condition corporelle pré-reproductrice sur la phénologie et le succès de reproduction des faucons pèlerins (Falco peregrinus) nichant dans l'Arctique canadien
Florence Lapierre-Poulin, Masters Student (Université du Québec à Rimouski)
Vulnerability of arctic fox (Vulpes lagopus) dens to climate change in the Canadian High Arctic
Don-Jean Léandri, Masters Student (Université Laval)
Kristen Peck, Masters Student (University of Alberta)
Nesting habitat and distribution of peregrine falcons (Falco peregrinus) in Nunavut
Pascal Royer-Boutin, Masters Student (Centre d'études nordiques)
Effets des cycles de lemmings sur le succès de reproduction d'oiseaux insectivores utilisant différentes stratégies antiprédateurs
Yannick Seyer, Masters Student (Centre d'études nordiques)
Stratégies de migration et de reproduction du labbe à longue queue (Stercorarius longicaudus) dans l'Arctique Canadien // Migratory strategies and reproduction of the long-tailed jaeger breeding in the Canadian Arctic
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Marie-Andrée Giroux, Post-Doctoral Fellow (Université du Québec à Rimouski)

Mikaël Jaffré, Post-Doctoral Fellow (Université du Québec à Rimouski)
Pascale Ropars, Post-Doctoral Fellow (Université du Québec à Rimouski)
Anne-Mathilde Thierry, Post-Doctoral Fellow (Université du Québec à Rimouski)
Helen Wheeler, Post-Doctoral Fellow (Université du Québec à Rimouski)
Philip Bertrand, Research Associate (Université du Québec à Rimouski)
Elise Bolduc, Research Associate (Université du Québec à Rimouski)
Marie-Christine Cadieux, Research Associate (Université Laval)
Nicolas Casajus, Research Associate (Université du Québec à Rimouski)
Aurélie Chagnon-Lafortune, Research Associate (Université du Québec à Rimouski)
Catherine Doucet, Research Associate (Université du Québec à Rimouski)
Frédéric Dulude-de-Broin, Research Associate (Université du Québec à Rimouski)
David Gaspard, Research Associate (Université du Québec à Rimouski)
Katherine Gavrilchuk, Research Associate (Université du Québec à Rimouski)
Magaly Oakes, Research Associate (Université du Québec à Rimouski)
Josée-Anne Otis, Research Associate (Université du Québec à Rimouski)
Myriam Trottier-Paquet, Research Associate (Université du Québec à Rimouski)
Michael Janssen, Technical Staff (Environment Canada - Science and Technology Branch)
Jake Russell Mercier, Technical Staff (Environment Canada - Science and Technology Branch)
Denis Sarrazin, Technical Staff (Centre d'études nordiques)

Northern HQP

Samuel Piugattuk, Northern Research Staff (Nunavut Arctic College)
Amanda Uttak, Northern Research Staff (Nunavut Arctic College)

ABSTRACT

Arctic ecosystems are undergoing major changes related to climate shifts. An understanding of this transformation is critical to anticipating ways in which potential negative effects may be mitigated and positive ones may become beneficial. To achieve this, we propose 4 specific objectives. First, we will monitor about 35 wildlife populations (mostly mammals and birds) at 12 study sites across a large latitudinal gradient in the Eastern Canadian Arctic (IRIS 2 region, main sites: Rankin Inlet, Coats Island, Southampton Island, Igloolik Island, Bylot Island). Monitored components are distributed through all levels of the food web, from plants to predators, to give the best-possible picture of ecosystem changes. Second, we will carry out field observations and experiments to unravel important relations between wildlife and climate. This will enhance our understanding of ecological processes determining the response of wildlife to climate shifts. Third, we will identify (through modeling) the ecosystem-scale exposures and sensitivities of the tundra to climate change. This is a necessary step to reach our fourth objective, namely to estimate and map, at a regional scale, the ecological vulnerability of the tundra to climate shifts. We will use one region particularly exposed to climate change (Northern Quebec, IRIS 4 region) as a first case study to map tundra vulnerability, and will then expand this work to larger areas, such as the Canadian Arctic. Our efforts to upscale our research from the species to the ecosystem level will constitute a major legacy of our project beyond 2018. We work in collaboration with many partners including Environment Canada, Government of Nunavut, Canadian Wildlife Service, Parks Canada, Nunavut Tunngavik Inc., Nunavut and Nunavik Wildlife Management Boards, Baffinland Iron Mines Corporation, Agnico Eagle Mines Limited, Ouranos Consortium, and the Hunters and Trappers Organizations of many Northern communities. We will provide critical wildlife and ecosystem-related knowledge necessary to conduct the Integrated Regional Impact Studies of the "Eastern Arctic" and "Eastern Subarctic", two of the four regions identified by ArcticNet for such assessments. While fostering strong ties and knowledge transfer with Inuit, our research will also provide training to a large number of Highly Qualified Personnel (including Northeners), who will then become uniquely positioned to meet the challenges arising from the rapid transformation of the North.

KEY MESSAGES

- Monitoring wildlife is required to assess ecosystem changes in the Arctic, whether they are caused by climatic variation, natural resources development or other anthropogenic activities.
- We monitor about 35 wildlife populations from the arctic tundra and marine ecosystems. This provides Canada with an important warning system regarding ecosystem changes in the Arctic. It also supports critical Arctic Council initiatives such as the Circumpolar Biodiversity Monitoring Program.
- We test ecological hypotheses through long-term field observations and detailed field experiments, some of them at the scale of the circumpolar Arctic. In particular, we generate new knowledge about the interactions that occur between species, about the role of sea ice and snow in wildlife ecology, and about the drivers of food webs dynamics in the terrestrial arctic ecosystems.
- Consequences of climate warming on wildlife should sometimes be negative and sometimes be positive, depending on the species that is considered. Those species most specialized for Arctic environments should be the most negatively affected.
- In the short term, increases in weather variability (rain in winter, heavy wet snowfalls in early spring, increased frequency of heavy summer rain) might have more negative influences than changes in average temperature or precipitation, although these averages may change abruptly.

- As the abundance of some species will increase while others will decrease, we expect important shifts in plant and wildlife species assemblages.
- A general northward movement of wildlife species is ongoing and should amplify in the next decades. This is mostly detected at the southern margin of the Arctic, for example in Nunavik.
- Species that play a key role in the organization of ecosystems, and thus influence ecosystem services such as provision of food to human communities, will likely change in many parts of the Arctic.
- Wildlife exploitation and food diversity of human communities in the Arctic depend on the composition and health of ecosystems. Therefore, assessing the vulnerabilities of ecosystems and their wildlife is needed to assess the vulnerability of human communities and establish environmental protection measures when needed.

OBJECTIVES

Our objectives for this ArcticNet Phase IV project are:

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.

INTRODUCTION

The effects of climate shifts (used here as a synonym of climate changes) are pervasive, occur at broad scales, and affect terrestrial and marine ecosystems. This in turn impacts the services that humans derive from their environment. While these general statements are true across the planet, they are particularly acute in the Arctic where snow and ice physically structure ecosystems, and where human communities are closely associated with wildlife. In this context, on-the-ground and efficient wildlife monitoring is critical to track ongoing ecological changes (Christensen et al. 2013), and excellent understanding of the relationships between species and climate is required to interpret and predict variation in wildlife populations (Van Oudenhove et al. 2014).

In their recent science plan for a Norwegian Climate-ecological Observatory for Arctic Tundra (COAT), Ims et al. (2013) have very well summarized the need for on-the-ground monitoring and understanding of ecological changes in the tundra. They note that “in context of the vastness of the circumpolar biome and its large internal variability, there are very few sites devoted to long-term research and monitoring” so that it is “crucial to establish scientifically robust observation systems to enable real time detection, documentation and understanding of climate impacts on arctic tundra ecosystems”. Although remote sensing is of increasing value to estimate coarse-scale ecological variables, most biodiversity remains unseen from space, so that on-the-ground research remains critical.

Our past work has given many examples of the value of field-based studies. For instance, our monitoring programs have revealed the heterogeneity of responses across trophic levels to recent climate warming in the High Arctic (Gauthier et al. 2013). In contrast to lower trophic levels (e.g. plants and arthropods), we found that several tundra vertebrates have shown little response to climate warming in the Canadian Arctic. This generates a high potential for disrupting biotic interactions in the near future, for instance by creating a mismatch between periods of high resource availability and periods of high resource demand for consumers (Miller-Rushing et al. 2010). At a broader level, we recently showed that predator-prey interactions were a dominant process for small to medium-size vertebrates of the tundra but that the strength of this interaction varied across a latitudinal gradient linked to temperature (Legagneux et al. 2014). We also found that changing sea ice conditions increased predation of ground nesting birds by polar bears (Iverson et al. 2014). This suggests that climate shifts may transform tundra and coastal food webs through multiple pathways, e.g. through changes in the timing of resource availability or in the species composition and abundance of predators.

While wildlife management usually focuses on some populations or species (those most valuable to humans), a growing number of stakeholders, managers and policy makers need information about components and drivers of change of ecosystems that involve higher levels of organization. For example, cumulative impacts arising from the simultaneous changes in climate, human demography, and industry development cannot be resolved without an ecosystem-based approach, which implies conservation of ecosystem structures, processes and interactions through sustainable use. As another example, large-scale developmental plans in the North (such as Québec's Plan Nord, Berteaux 2013) now entail land-conservation initiatives to protect biodiversity and sustain the ecological and cultural integrity of the region.

It has thus become clear that ecosystem-scale investigations are now needed to build a more comprehensive picture of ecological changes that will contribute to the future state of the Arctic and to the services that ecosystems provide to humans (Montoya and Raffaelli 2010). In the last years, a massive effort has been coordinated by the biodiversity working group of the Arctic Council to summarize the status and trends of Arctic biodiversity. While a key finding of this Arctic Biodiversity Assessment (Meltofte et al. 2013a) is that “Climate change is by far the most serious threat to Arctic biodiversity and exacerbates all other threats”, one of the key recommendations outlined in the Report for Policy Makers (Meltofte et al. 2013b) is “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 (Van der Putten et al. 2010). Scaling-up research from the species to the ecosystem-level thus entails new approaches.

Increasing and updating the observational basis needed to address the ecosystem-level questions raised by climate change (and modernization) in the Arctic is a major objective of ArcticNet. This project works towards improved wildlife monitoring and ecological understanding in the Eastern Canadian Arctic, and develops new approaches and new knowledge regarding ecosystem-level impacts of climate change.

ACTIVITIES

Time frame and study area: Field work was carried out from May to September 2015 at East Bay (Southampton Island), Rankin Inlet, Mary River (Milne Inlet to Steensby Inlet), Iglloolik, Kugluktuk, Baker Lake, Digges Island, Coats Island, Greenland, Ellesmere Island and Bylot Island. Boat-based bird and polar bear research was carried out in July 2015 along the south coast of Hudson Strait in partnership with the community of Cape Dorset. The Greenland and Ellesmere fieldwork was carried out in August and September 2015 at the northern parts of these islands using a Swedish Icebreaker, in partnership with the communities of Grise Fjord, Kangerlussuaq and Thule.

Research: Intensive field work was done and detailed analyses of collected data (capture and marking of wildlife, nest abundance, nest survival, digital pictures, acoustic recordings, locations of animals and movement behavior, avian and mammal distance sampling, avian disease sampling) and samples (tissues from wolf, wolverine and bear carcasses, lemming winter nests, predators and prey faeces, predator skulls, bird of prey pellets, plant above-ground biomass, insects and spiders, wildlife blood, hairs/feathers) were performed. Particular effort was made to synthesize existing data and integrate them into circumpolar research efforts. This resulted in the following investigations:

Weather

- Retrieval of annual weather data from four automated weather stations on Bylot Island, two at Rankin Inlet, two at East Bay (Southampton Island), and one at Coats Island. One semi-automated station was used on Igloolik, Greenland, and Ellesmere.
- Retrieval of annual snow condition data from two automated environmental monitoring stations on Bylot Island.

Plants

- Monitoring of plant primary production and goose grazing impact in wetland habitats at Bylot Island (24 exclosures).
- Monitoring of lemming grazing impact at Bylot Island (16 exclosures).
- Monitoring of arthropods and goose browsing in six plots in Igloolik.
- Long-term set-up of an ITEX site on Igloolik.
- Plant species collection and range classification on 12 islands in Hudson Strait.

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 at Igloolik Island, Greenland and Ellesmere.

Birds (raptors)

- Monitoring of ca. 350 peregrine falcon, gyrfalcon and rough-legged hawk nest sites at Rankin Inlet, Igloolik, Kugluktuk, Baker Lake and Mary River.
- Monitoring of chick growth rate from 30 raptor nests at Rankin Inlet.
- Observation of peregrine behavior, breeding phenology, causes of mortality and identification of marked birds using infrared-triggered cameras and direct observation.
- Banding of 120 peregrines and rough-legged hawks at Rankin Inlet and Mary River.
- Monitoring of the reproductive activity of 21 nests of rough-legged hawks (among 80 known potential nesting sites visited), four nests of peregrine falcons (among eight known potential nesting sites visited), and one nest of gyrfalcon at Bylot Island.
- Monitoring of body condition and stress levels in peregrine falcons through collection of 18 three-minute post-capture blood samples for analysis of corticosterone, triglycerides, and B-hydroxybuterate.
- Marking of two adult rough-legged hawks with satellite transmitters at Bylot Island.
- Sampling of snowy owl and hawk pellets (>100) at Igloolik Island.
- Acoustic recording of biodiversity at snowy owl and hawk territories on Bylot.

Birds (shorebirds and passerines)

- Monitoring of ca. 100 shorebird nests and 90 passerine nests at Bylot Island.
- Marking of ca. 60 shorebirds and ca. 50 passerines at Bylot Island.
- Deployment of 43 geolocators on shorebirds (nine on American golden-plovers and 34 on common-ringed plovers) and recovery of previously deployed geolocators from eight

American golden-plovers and seven common-ringed plovers on Bylot Island.

- Monitoring of the growth rate of 75 known-aged snow bunting chicks from 23 nests on Southampton Island.
- Monitoring of 111 shorebird and 50 passerines nests at Igloolik Island.
- Marking of ca. 50 shorebirds, with 25 equipped with geolocators (GLS) at Igloolik Island. Recovery of 5 GLS from American Golden Plovers.
- Beginning of a monitoring of snow bunting nest survival at Igloolik Island.
- Monitoring of body condition of red phalaropes at Igloolik Island.
- Monitoring of mercury levels in shorebirds at Igloolik Island.
- Distance sampling at-sea and in the tundra for northern Ellesmere and Greenland of early migrants either bound to Europe or to the Americas.
- Acoustic recordings of shorebird and passerine phenology at Igloolik and Bylot.

Birds (geese and seabirds)

- Monitoring of reproductive activity of 347 nests of snow geese at Bylot Island.
- Monitoring of the reproductive activity of 38 nests of long-tailed jaegers, 2 nests of parasitic jaegers, and 29 nests of glaucous gulls at Bylot Island.
- Banding of 28 long-tailed jaegers, deployment of 20 geolocators on jaegers and recovery of 5 previously deployed geolocators at Bylot Island.
- Banding and re-sighting of 200 adult eider ducks on Southampton Island to estimate annual survival of birds in relation to disease, harvest, and weather conditions.
- Capture and banding of 3675 snow geese with leg bands, including 587 adult females with neck-collars, at Bylot Island to monitor survival and recruitment.
- Collection of blood samples from 200 eider ducks on Southampton Island to assess links between hormones, body condition, and vulnerability to avian cholera.
- Ongoing satellite tracking of common and king eiders to determine marine habitat use in the Canadian Arctic and West Greenland.
- Deployment of 7 satellite tags on herring gulls at East Bay Island to monitor their migratory movements in relation to diet composition and contaminant levels.
- Surveying of common eider breeding colonies in Digges Sound to evaluate the severity and geographic scope of avian cholera and polar bear nest predation.
- GPS tracking of 74 thick-billed murres from Digges Island nesting colony to identify key foraging habitat areas during the breeding season.
- Monitoring of the reproductive activity of 10 nests of long-tailed jaegers and parasitic jaegers at Igloolik Island.
- Distance sampling at-sea and in the tundra for northern Ellesmere and Greenland of early migrants either bound to Europe or to the Americas.
- Collection of ca. 500 faeces from ptarmigans and geese to measure their diet.

Mammals

- Monitoring of 116 fox dens and of 26 arctic fox yearly movements at Bylot Island using Argos satellite transmitters.
- Monitoring of long-range movements (> 2000 km) of arctic foxes across Nunavut.
- Monitoring of lemming abundance and demography at Bylot Island (582 winter nests

sampled; live-trapping of 328 brown lemmings and 27 collared lemmings during 4100 trapping days; snap-trapping of 19 brown lemmings and 4 collared lemmings during 2100 trapping-days; counts of burrows and feces at 192 pairs of 60 m-transects).

- Monitoring of lemming abundance at Rankin Inlet (500 snap trapping days).
- Monitoring of 21 ermine dens and 50 shelter boxes at Bylot Island.
- Observation of fox behaviour on Bylot using 50 infrared-triggered cameras.
- Determination of diet and reproductive effort of >100 wolverines and wolves by analysing stomach contents and reproductive tracks of animals harvested in Nunavut during 2012-2014.
- Observation of bird nest predation and disturbance (e.g. polar bear, arctic fox, weasel, black flies, human disturbance) using infrared-triggered cameras.
- Monitoring of > 25 dens of fox and wolves in Igloolik, Northern Greenland and Ellesmere with sampling of faeces and diet remains (>1000 samples).
- Collection of > 1000 faeces from ermines, brown and collared lemmings, arctic wolves, arctic hare, muskoxen, caribou, and wolverines in Igloolik, Northern Greenland and Ellesmere to track diet.
- Biopsy darting of five polar bears along the south coast of Baffin in collaboration with Cape Dorset HTO to evaluate through genetics how many bears use the area in July.

Syntheses

- Synthesis across several circumpolar study sites of climatic and ecological factors structuring tundra ecosystems.
- Participation to the implementation of the Circumpolar Biodiversity Monitoring Program coordinated by the Conservation of the Arctic Flora and Fauna initiative.
- Consolidation of the Circumpolar Arctic Fox Research Network to facilitate data synthesis on this species, recognized as priority focal ecosystem component by the Circumpolar Biodiversity Monitoring Program.
- Synthesis of the main results generated by the long-term monitoring of peregrine falcons nesting in the eastern Canadian Arctic
- Participation to the Tundra Conservation Network to understand and predict the effects of climate change on Arctic ecosystem processes, specifically the tundra food web with Gyrfalcons, ptarmigan, and vegetation as integral components.
- Synthesis across several circumpolar study sites through involvement in the Circumpolar Seabird Working Group of the Arctic Council.

RESULTS

The results of our first project objective (to monitor about 35 wildlife populations at 12 study sites) are described above under Activities. We highlight, however, that we added a new monitoring site at Igloolik Island (Nunavut) (Figure 1). This very efficiently complements our network of monitoring sites in the Canadian Eastern Arctic.

Our second project objective (to better understand six key processes linking climate shifts to wildlife population dynamics and species interactions) focused on (1) bird nesting survival, (2) bird phenology, (3) wildlife breeding habitat, (4) predation rate, (5) predator distribution, and (5) animal movement. We report here results dealing with (2) through a study on peregrine falcons and a study on snow geese, results dealing with (4) through a study on brown lemmings, and results dealing with (5) through a study on shorebirds and geese.

Figure 1. Location of Igloolik Island as seen from the northern tip of Canada (A), map of Igloolik regional investigation with the intensive nest search area in red (B), means of transportation and strong interactions with the community close to our camp (C, D), field logistic supported by aircrafts of the Polar Continental Shelf Program (E), monitoring of main predators such as the arctic fox (F) and ermine (G), monitoring of bird migration with geolocators and bands (H), monitoring of vertebrate phenology with automatic acoustic recordings (I), including the Lapland longspur (J) for which songs and calls are tracked continuously. Maps: Google Earth. Pictures: Nicolas Lecomte.

Bird phenology: egg-laying in peregrine falcons

Timing of reproduction in birds is known to influence reproductive success, and can also affect fitness and reproductive investment. In peregrine falcons, Anctil et al. (2013) indicated that early lay date was amongst the most important variables that influenced survival of nestlings, and an analysis of clutch size in peregrine falcons showed that breeding pairs that laid early were also more likely to lay larger clutches (Figure 2). The probability of laying a four-egg clutch was on average 0.93 for the earliest breeders and 0.01 in the latest breeders.

Triglycerides are the main constituent of body fat in humans and animals; they are indicators of fat metabolism and can be used in birds to assess pre-laying condition. Triglyceride concentration in blood plasma is positively correlated with short-term changes in body mass, and can provide insight into fattening rate in birds. An analysis of triglyceride in the blood plasma of female peregrines showed that individuals with high concentrations of plasma triglyceride laid earlier than those with low levels of plasma triglyceride (Figure 3).

Bird phenology: consequences of trophic mismatch on snow geese

We found that snow geese are only partially able to adjust their breeding phenology to compensate for climate-induced annual changes in the timing of high quality food plants. In most years, the peak of nitrogen concentration in plants, an index of their nutritive quality for geese, occurred earlier than the date of peak hatch of goslings, leading to a mismatch between the two. This mismatch was more important (up to 20 days) in years with warm springs and an early snow melt because plant growht advanced more than the nesting phenology of geese. We showed that this had negative consequences for geese as gosling body mass size at fledging was reduced when trophic mismatch was high, particularly when the difference between date of peak nitrogen concentration and hatching was greater than 9 days (Figure 4).

Predation: seasonal demography of cyclic lemming populations

Long-term population studies of brown lemmings on Bylot Island allowed us to determine that lemming population declines after a peak occurred between the summer and winter period and not during the winter.

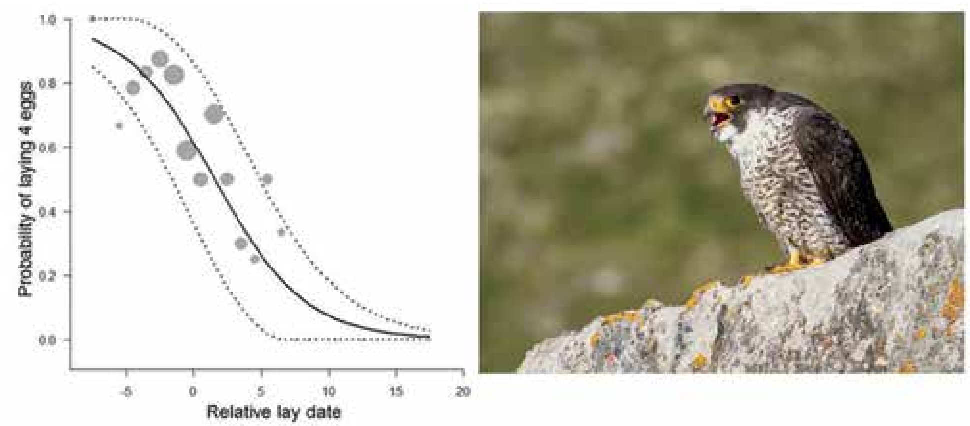

Figure 2. Probability of laying a clutch of four eggs in arctic-nesting female peregrine falcons in relation to relative lay date, with values standardized relative to the yearly median. The solid black line represents fitted logistic regression, 95% confidence intervals are represented by dashed lines, and symbol sizes are proportional to log(N+1). Peregrine picture: Nicolas Bratette.

In winter, lemming population growth was driven by changes in late summer and winter reproduction whereas during the summer, population growth was driven by change in survival but not in fecundity or proportion of juveniles (Figure 5).

Weather parameters only affected early summer survival as lemming survival was positively related to snow depth at the onset of melt but negatively related to rainfall during that period (Figure 6).

Predator distribution: relationships between shorebirds and overabundant geese

Recent increases in arctic goose populations have impacted tundra ecosystems directly through vegetation degradation. Such increase can also feed indirect interactions through shared predators, which can generate negative impacts on other wildlife species such as shorebirds (Figure 7).

We analyzed six years of data on the distribution and abundance of nesting American Golden-Plovers and nest predators, as well as shorebird nest depredation risk (using artificial nests). Data were collected at a large spatial scale on Bylot Island and along transects

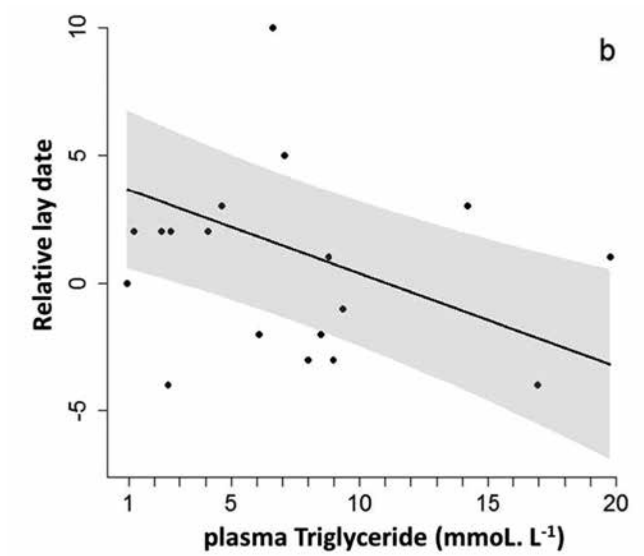

Figure 3. Relationship between plasma triglyceride and relative lay date (i.e., lay date standardized to the yearly median) in female peregrine falcons (i.e., females captured between 10 and 20 days before egg-laying) in Nunavut. The shaded grey area represents 95% confidence interval.

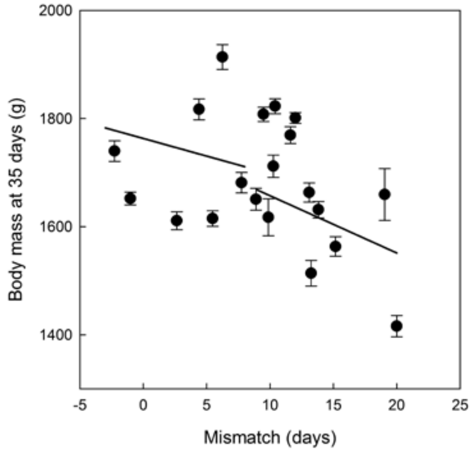

Figure 4. Relationships between body mass of individual goslings adjusted at 35 days and annual mismatch between hatch date of goslings and date of peak nitrogen concentration in plants on Bylot Island, Nunavut, from 1991 to 2010 (from Doiron et al. 2015). © 2015 John Wiley & Sons Ltd.

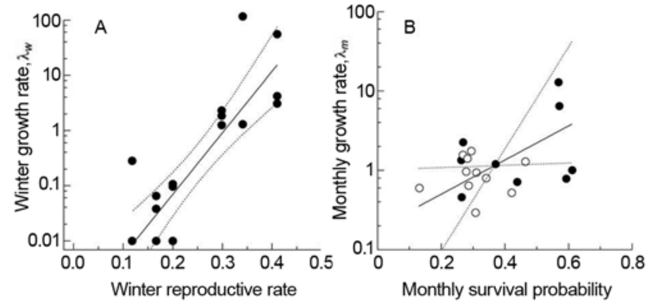

Figure 5. Relationships between (A) winter population growth rate (λw, from August of year y to June of year y+1) of brown lemmings and reproductive rate in winter nests and (B) monthly population growth rate (λm) of brown lemmings and survival probability over the same period for the periods June-July (filled circles) and July-August (open circles) on Bylot Island, NU. The regression (solid lines) and 95% confidence intervals (dotted lines) are presented (from Fauteux et al. 2015). © 2015 John Wiley and Sons © 2015 Fauteux, Gauthier, Berteaux. Journal of Animal Ecology © 2015 British Ecological Society.

located up to 22 km from the centroid of the snow goose colony.

We found evidence that the goose colony had tremendous influence on the spatial distribution and abundance of nest predators and nesting plovers. Occurrence of predators decreased (Figure 8), while nesting plover occurrence increased (Figure 9) with the distance from the goose colony. As lemmings are the preferred prey of arctic foxes, these effects were more pronounced in years with low lemming density. Shorebird nest depredation risk also decreased with distance from the colony (reduction of up to 7% per 10 km away from the centroid of the goose colony).

The results of our third project objective (to identify, through modeling, the ecosystem-scale exposures and sensitivities of the tundra to climate change) are just now starting to build up, as shown below.

We developed a model of species interactions with increasing levels of temperatures and biomass of prey that are driven by human activities (migrating geese using agricultural lands on their way to their tundra breeding site). This model is derived from our long-term empirical effort to measure arctic fox and goose interactions in varying environmental conditions (e.g. Giroux et al. 2012; Legagneux et al. 2014). Following our empirical measures and model, we detected that the availability of migrating birds could allow fox populations to reach larger abundance than expected from the primary productivity of the tundra ecosystem or from an increasing air temperature.

Climate-driven poleward shifts, leading to changes in species composition and relative abundances, have been recently documented in the Arctic. For

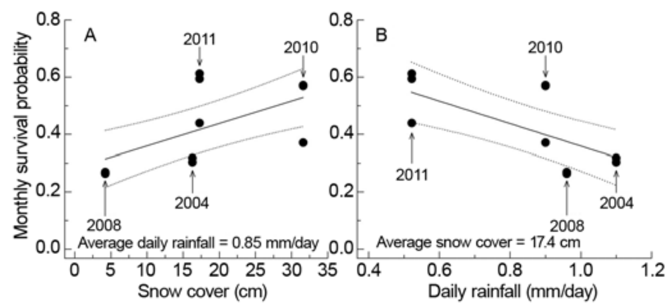

Figure 6. Relationships between early summer (June to July) survival probability of brown lemmings and (A) spring snow depth and (B) mean daily rainfall on Bylot Island, Nunavut. The regression (solid lines) and 95% confidence intervals (dotted lines) are presented (from Fauteux et al. 2015). © 2015 John Wiley and Sons © 2015 Fauteux, Gauthier, Berteaux. Journal of Animal Ecology © 2015 British Ecological Society.

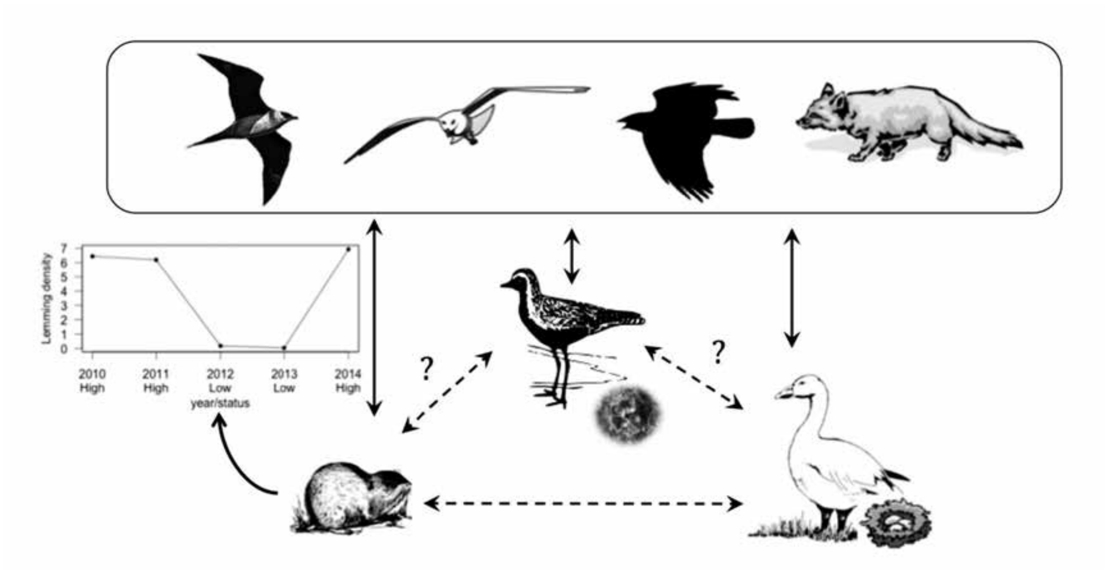

Figure 7. Simplified trophic web of the Bylot Island ecosystem illustrating the direct (solid lines) and indirect (dashed lines) links between overabundant snow geese, shorebirds and cyclic lemming populations sharing the same predators.

example, black bears are a typical boreal species that are now becoming more common in the tundra of Nunavik, Quebec. Among the fastest moving species are thus boreal generalists. They are expected to affect tundra food web structure and ecosystem functioning substantially. We started to address structural changes at the food web level induced by poleward shifts via topological network analysis of highly resolved boreal and arctic food webs. As a first step, we summarized a large quantity of disparate information (including expert knowledge) to build a simplified food web of the Low Arctic tundra of Nunavik (Figure 10). We hypothesize that northern shifts in species distributions have the potential to change arctic tundra food web structure considerably, with implications for ecosystem dynamics and functioning.

Results of our fourth project objective (to estimate and map, at a regional scale the vulnerability of the tundra to climate shifts) will only become available once we have made substantial progress toward our third objective.

DISCUSSION

Bird phenology: egg-laying in peregrine falcons

Findings on the phenology of reproduction in peregrine falcons demonstrate that early initiation of reproduction in peregrine falcons is one of the most important factors that can influence reproductive success. These findings support predictions of theoretical models that energy allocation during the pre-laying period has a crucial impact on individual-based decisions regarding timing of breeding, and ultimately on reproductive output. In addition, these findings highlight that breeding success in peregrine falcons is also related to factors that influence individuals prior to the breeding season, for example during migration.

Bird phenology: consequences of trophic mismatch on snow geese

The phenomenon of trophic mismatch is widespread and has negative impacts on species in multiple biomes (Brooks et al. 2015). However, it's impacts may be

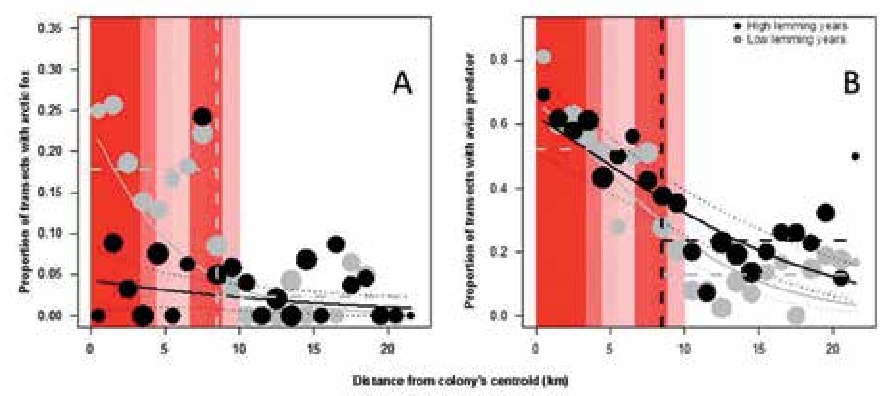

Figure 8. Occurrence of arctic fox (A) or avian predators (B) on transects according to the distance from the centroid of the goose colony and the abundance of lemmings (years of high lemming density are in black and years of low lemming density are in grey). The probability of being inside the colony is represented by the color ramp (probability to be inside ranged from 100% in red to 0% in white). Dots represent mean proportions and the size of the dots is proportional to log (N). The vertical dashed line was obtained from a segmentation analysis and the horizontal dashed lines represent the mean occurrence above and below the segmented point.

amplified in the Arctic due to the high seasonality of resources, short breeding seasons, and intense climate warming, as has been shown in Arctic-nesting shorebirds (McKinnon et al. 2012) and migratory caribou (Post and Forchhammer 2008). Our study provides additional evidence that trophic mismatch could have important consequences on the population dynamics of long-distance migrants by affecting the quality of their food supply. This adds to the growing body of evidence that some of the most severe impacts of climate warming on Arctic species may be indirect, through disruptions of the synchrony in the phenology of species at different trophic levels (Miller-Rushing et al. 2010). This emphasizes the importance of taking a multi-species food web approach when examining the consequences of environmental change on organisms.

Predation: seasonal demography of cyclic lemming populations

We found an interesting contrast between summer and winter in the demographic factors associated with lemming population changes. During the summer, population growth was driven by change in survival but not in fecundity, whereas in winter it was driven by changes in reproduction. Since predation is the main cause of mortality of lemmings (Therrien et al. 2014), this suggests that predation drives summer population growth and is the major factor causing fall population crashes during peak years. In contrast, high winter reproduction appears to be the main driver of the increase phase of the population cycle and thus of population irruptions.

Our results also suggest that climatic factors may affect summer survival of lemmings. However, it is possible that the high early summer survival in years of deep snow cover is actually an indirect effect mediated through predation because deep snow will delay snow-melt and could allow lemmings to move for a longer period of time under the protective snow cover (Gilg et al. 2009). The general decline of snow cover observed in the Canadian Arctic (Derksen and Brown 2012) may be of particular concern for lemming populations because it may extend their period of vulnerability to predators during the snow-free period, while reducing their potential for population growth under the snow.

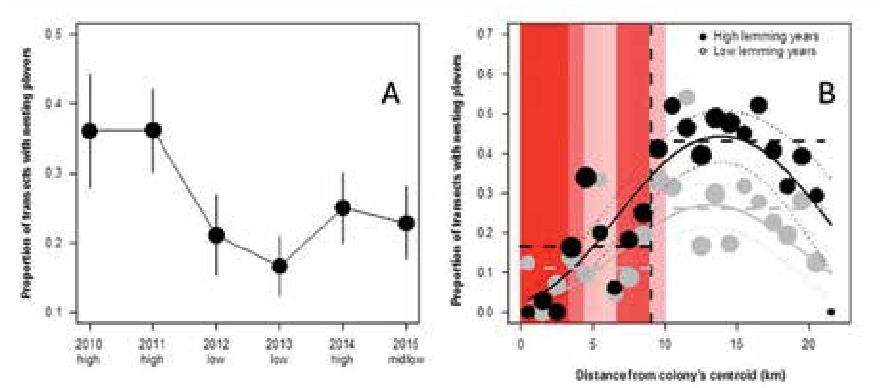

Figure 9. Proportion of nesting American Golden-Plovers sighted on transects depending on the year considered (A) and occurrence of nesting American Golden-Plovers on transects according to the distance from the centroid of the goose colony and lemming density (high lemming density is in black, low lemming density is in grey). The probability of being inside the colony is represented by the color ramp (probability to be inside ranged from 100% in red to 0% in white). Dots represent mean proportions and the size of the dots is proportional to log (N). The vertical dashed line was obtained from a segmentation analysis and the horizontal dashed lines represent the mean occurrence above and below the segmented point.

Predator distribution: relationships between shorebirds and overabundant geese

The greater snow goose population has increased exponentially at the end of the 20th century, primarily due to new habitats (intensively cultivated land) created by human activities in temperate regions (Gauthier et al. 2005). Greater snow geese were declared overabundant in 1998 due to the potential impacts of their rapidly growing population on wetland habitats and on other species. Though the impacts of geese on their arctic breeding habitats have been well described, there is a poor understanding of the interactions between geese and sympatric bird species.

There are some indications in the literature that large goose colonies could negatively impact shorebirds. For instance, multiple surveys on Banks Island have revealed that the density of shorebird species is inversely related to distance from the goose colony (Hines 2010). Similarly, semipalmated sandpipers have been excluded from La Pérousse Bay with a concurrent increase in snow goose abundance (Jehl Jr 2007). Such findings suggest potential exclusion of shorebirds by geese mediated by habitat degradation or predation. Although potentially important, the indirect impacts of geese on other prey species that share the same predators, such as shorebirds, are still very poorly understood and are likely underestimated (McKinnon et al. 2013).

Predation avoidance was recently highlighted as one of the main drivers explaining why some birds migrate to the far north for the breeding season (McKinnon et al. 2010). Our study on Bylot Island provides evidence that, during the breeding season, overabundant arctic-nesting snow geese reduced the amount of enemy-free space in the arctic tundra, leading to a higher depredation risk for shorebird nests within and in the vicinity of a goose colony. Even if the magnitude of the impact of geese on vulnerable arctic shorebirds could be low at the global scale, our study revealed that the negative impacts at the local scale (e.g. Bird Sanctuary or National Park) could be highly significant.

Exposures and sensitivities of the tundra to climate change

Findings on arctic ecosystems suggest that increasing input of migratory birds that are driven by agricultural changes (subsidies) can modulate the tundra sensitivity to increasing temperatures (Giroux et al. 2015). Therefore, studying simultaneously the multiple forces

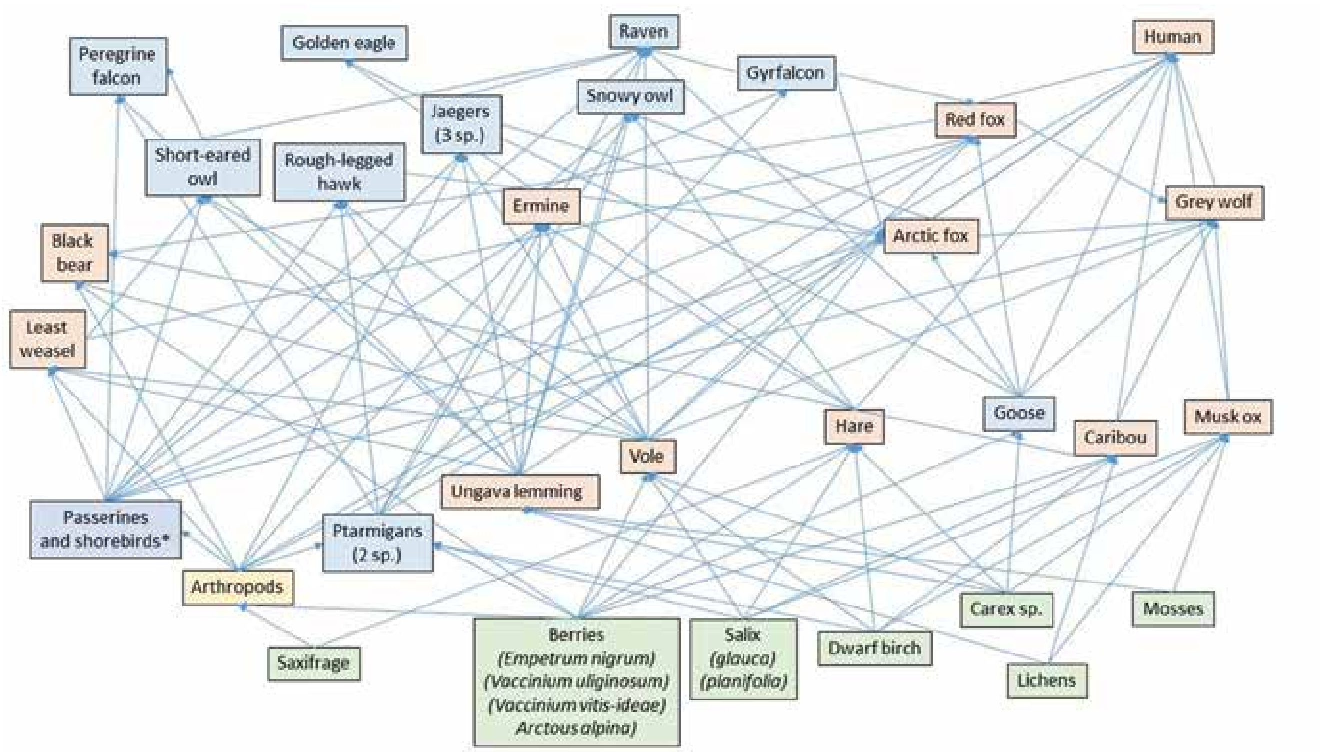

Figure 10. Who eats Who: simplified food web of the tundra of Nunavik showing the many connections between mammals (including humans), birds, arthropods (insects and spiders), and plants. Although not shown, freshwater and marine species do maintain important trophic relations with tundra species.

impacting the tundra ecosystems may be essential to decipher the drivers of tundra vulnerability to climate changes.

We have selected Northern Quebec (IRIS 4), where impacts from climate changes are particularly acute, as first case study to investigate the vulnerability of the tundra food web to climate change. Although our efforts in this direction are still at a very early stage, research conducted in other arctic ecosystems, such as the Barents Sea (Kortsch et al. 2015) suggests that considerable differences might exist in structural properties and link configuration between the boreal and arctic food webs (the latter being more modular and less connected). The main characteristic of the boreal species moving poleward into the arctic tundra might be high generalism, a property that might increase connectance and reduce modularity in the arctic tundra foodweb. Future progress will indicate whether new species reaching the tundra change arctic food web structure considerably, with implications for ecosystem dynamics and functioning.

CONCLUSION

Our work intensifies wildlife monitoring in the Canadian Arctic through the addition of new monitored populations and new study sites across a large latitudinal gradient, and through the development of research activities linking climate to food web functioning.

Our project is one of 10 projects in IRIS 2 and contributes the most data and knowledge to the wildlife chapter of the IRIS 2 report. Our work during 2015-2016 was a natural extension of the research we did within ArcticNet during the last 10 years. We are maintaining 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. These additional monitoring efforts provide much needed observation stations and results for then Integrated Regional Impact Assessments. Altogether, this continues to strengthen the fundamental objective of the IRIS framework.

In addition, we have started to integrate the information from our existing long-term field studies via predictive models of ecosystem exposure, sensitivity, and vulnerability (objectives 3 and 4). Such exercise, combining our field knowledge with existing literature data, governmental information and expert knowledge, should be particularly relevant to conduct Integrated Regional Impact Assessments. Some of the products we intend to generate (e.g., ecosystem vulnerability maps) are particularly well-suited to conducting regional impact studies and assessments.

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Population Dynamics and Predator-Prey Relationships in Migratory Caribou of the Québec-Labrador Peninsula in the Context of Climate and Anthropogenic Changes

Project Leader

Steeve Côté (Université Laval)

Collaborators

Stéphane Boudreau (Université Laval)
Vincent Brodeur (Ministère des Ressources Naturelles et de la Faune)
Nicholas Coops (University of British Columbia)
Ben Dalziel (Cornell University)
Christian Dussault (Université du Québec à Rimouski)
Marco Festa-Bianchet (Université de Sherbrooke)
Paul Grogan (Queen's University)
Matthew J. Kauffman (University of Wyoming)
Susan Kutz (University of Calgary)
Nicolas Lecomte (Université Laval)
Jennifer Mitchell (Nunatsiavut Department of Lands and Natural Resources)
Loïc Pellissier (Université de Lausanne)
John Pisapio (Government of Newfoundland and Labrador (Environment and Conservation)
Isabelle Schmelzer (Government of Newfoundland and Labrador (Environment and Conservation)
Martin-Hugues St-Laurent (Université du Québec à Rimouski)
Joëlle Taillon (Université Laval)
Jean-Pierre Tremblay (Université Laval)
Glenn Yannic (Université Laval)

HQP

Michaël Bonin, Doctoral Student (Université Laval)
Mael Le Corre, Doctoral Student (Université Laval)
Influence of resource availability and anthropic disturbances on habitat selection and space use of migratory caribou
Sabrina Plante, Doctoral Student (Université Laval)
Barbara Vuillaume, Doctoral Student (Université Laval)
Environmental determinants of migratory caribou survival
Edouard Bélanger, Masters Student (Université Laval)
Brett Allen Campeau, Masters Student (Université Laval)
Clara Morrissette-Boileau, Masters Student (Université Laval)
Mathieu Leblond, Post-Doctoral Fellow (Université Laval)
Julien Hénault-Richard, Research Associate (Université Laval)
Caroline Hins, Research Associate (Université Laval)
Sarah McCarty, Research Associate (Government of Newfoundland and Labrador (Environment and Conservation))
Dominic Grenier, Technical Staff (Ministère des Forêts, de la Faune et des Parcs)
Charles Jutras, Technical Staff (Ministère des Ressources Naturelles et de la Faune)
Stéphane Rivard, Technical Staff (Ministère des Ressources Naturelles et de la Faune)
Philippe Demers, Undergraduate Student (Université Laval)

Northern HQP

Ellen Avard, Northern Research Staff (Makivik Corporation)
Peter May, Northern Research Staff (Makivik Corporation)
Stas Olpinski, Northern Research Staff (Makivik Corporation)
Claude Tremblay, Northern Research Staff (Centre d'études nordiques)

ABSTRACT

The proposed research builds upon a collaboration between academic scientists, government biologists, aboriginal organizations and private industry to better understand the ecology and conservation of migratory caribou, a key component of the ecology, economy and culture of Canada's north. We will examine how climate change, habitat modifications, industrial development, sport and subsistence hunting interact with changes in predation, population phases of caribou demography and environmental variability to affect the abundance and distribution of two herds of migratory caribou that are showing contrasted population trajectories. Our research team will combine state-of-the-art satellite technology, isotopic and nutritional analyses with innovative scientific hypotheses, statistical and modelling techniques, to provide government, Aboriginal organizations and industry with reliable information on minimizing the impacts of industrial activities and harvest on caribou population ecology. Our results will be essential to ensure the continued sustainable harvest of caribou by subsistence and sport hunters. Because our research will be based on a proven ability to monitor a very large sample of instrumented caribou and will test several innovative hypotheses, our team will continue to provide contributions of high scientific merit, advancing our understanding of northern ecology. We will also provide training for about seven graduate and 6-8 undergraduate students, on subjects about and within a northern ecosystem where advanced knowledge in ecology and conservation are in very high demand.

KEY MESSAGES

- Accessibility to the hunting territory, via roads and outfitter camps, and visibility increase caribou vulnerability to sport hunting.
- Our results suggest a spatial dissociation between use by caribou and hunters, and harvest distribution.
- Ice has a positive influence on caribou movement rates and directionality. Movement rates of caribou were significantly higher on ice and during detours than elsewhere in the study area.
- Caribou selected ice and avoided water when moving across or in the vicinity or large water bodies.
- The Rivière-George caribou herd has demonstrated a decrease in the size of its summer range and a change in preferred summer movement pathways over the 1991-2011 period.
- Changes in summer range of the Rivière-George herd appear to reflect the demographic trends and may be related to changes in green forage availability.
- Preliminary analyses for the Rivière-aux-Feuilles herd for the period between November 2014 and October 2015 indicate an overall low survival rate and suggest a higher survival rate for adult females than males.
- Yearling survival appears more affected by climate conditions than adult survival.
- Preliminary results suggest migratory behavior of wolves from the range of the Rivière-aux-Feuilles caribou herd. Wolves do not appear to maintain annual territories but follow caribou in their migrations.
- Recent fieldwork revealed a low abundance of wolves on the Rivière-George herd range, most likely indicating a numerical response of wolves following the 98% reduction in the abundance of the Rivière-George caribou herd.

OBJECTIVES

Our multidisciplinary research program seeks to better understand the ecology and conservation of two herds of migratory caribou (*Rangifer tarandus*) in northern Québec and Labrador, the Rivière-George and the Rivière-aux-Feuilles herds. More specifically, we aim:

1. to determine cumulative impacts of human disturbance on habitat selection and demography of migratory caribou (Ph.D. 1 – S. Plante);
2. to study the spatiotemporal use of migration corridors by caribou (Postdoc – M. Leblond);
3. to evaluate changes in space use of caribou using remote sensing (M.Sc. 1 – B. Campeau);
4. to identify the determinants of caribou survival for all sex-age classes (Ph.D. 2 – B. Vuillaume);
5. to study interactions between caribou and its predators (Ph.D. 3 – M. Bonin, Ph.D. 4 – B. Rogers); and
6. to determine the indirect consequences of the intensification of the shrub layer on summer food resources of caribou (M.Sc. 2 – to be determined).

INTRODUCTION

The conservation and management of wildlife populations represent a central issue in northern areas of Canada, that are increasingly affected by human development and threatened by climate change. Migratory caribou is a key element of the ecology of the north, where it is central for the culture and the economy of communities. Despite substantial research efforts, the factors explaining variations in the abundance of migratory caribou are not fully understood, making their management problematic (Festa-Bianchet et al. 2011). Several populations of caribou are decreasing and human disturbance and climate change are among the major proposed causes of the current circumpolar decline (Vors and Boyce 2009).

Two major migratory caribou herds inhabit northern Quebec and Labrador, the Rivière-George and Rivière-aux-Feuilles herds. These herds have recently undergone major demographic change with high temporal variations. Changes in the abundance and distribution of caribou may have serious impacts for indigenous people and the outfitting industry. The caribou are an important food source for the Inuit, Cree, Naskapi and Innu, who harvest more than 10,000 caribou per year. Northern Quebec and Labrador could be subject to radical increases in industrial activities with their high mineral potential and the development of the Plan Nord. These developments could have significant ecological and demographic consequences for migratory caribou. In addition, average temperatures in the Arctic have increased nearly twice as fast as the global average over the last 100 years, and significant additional warming at these latitudes is expected (Brown et al. 2012, IPCC 2014). Following the drastic reduction of populations, especially for the Rivière-George herd with a decrease of 98% of its abundance since the early 1990s, we do not know if the population is currently sustainable. Only sound knowledge on population dynamics would ensure the sustained use of the resource. Current knowledge is inadequate to anticipate changes in abundance of caribou, or predict an eventual return of abundant populations. To improve the management and conservation of migratory caribou, a long-term research program is essential. Indeed, the characteristics of caribou (e.g. long life expectancy, variable vital rates) necessarily involve high temporal variations. Furthermore, to understand the impact of density-dependent and independent factors (e.g. climatic factors), it is necessary to analyze a long-time series encompassing a wide range of conditions.

Our initiative seeks to advance our understanding of four major aspects of caribou conservation: 1) the cumulative effects of human activities (e.g. mining, linear structures) on caribou space use and survival, 2) predator-caribou interactions, 3) population dynamics, to maintain subsistence and sport hunting, and finally, 4) the impacts of climate change and demographic changes on caribou habitat. Migratory caribou are central to the economy and traditional life of Northern peoples and an understanding of their demography in a context of climate change and industrial development is essential for the IRIS framework of ArcticNet.

ACTIVITIES

Fieldwork activities

- **March, April and June 2015 –** We conducted several captures of caribou, wolves and black bears on the Rivière-aux-Feuilles and Rivière-George ranges to increase the number of individuals wearing GPS collars:
  - » capture and marking of 15 caribou from the Rivière-aux-Feuilles herd with GPS collars. Replacement of eight defective collars on females of known age;
  - » capture and marking of 23 caribou from the Rivière-George herd with GPS collars;
  - » capture and marking of six wolves from the range of the Rivière-aux-Feuilles herd with GPS collars; and
  - » capture and marking of one wolf and six black bears from the range of the Rivière-George herd with GPS collars.
- **June to August 2015 –** We conducted fieldwork for the vegetation and climate experiments at Deception Bay:
  - » installation of a new experimental design to manipulate snow cover and shading;
  - » monitoring of floristic composition in the experimental plots; and
  - » harvesting of biomass samples of key species (e.g. dwarf birch, grasses and sedges) to analyze the chemical composition.
- **October 2015 –** We continued the classification of more than 4300 caribou from the Rivière-aux-Feuilles herd and 1600 caribou from the Rivière-George herd. Monitoring of reproductive success of radio-collared female caribou from both herds.
- **Autumn 2015 and Winter 2016** – We developed a recovery system of predator carcasses with Aboriginal people to collect tissue samples and digestive tracts.
- **January and February 2016 –** Capture of wolves and caribou in the Rivière-aux-Feuilles winter range.

Meetings, conferences and workshops

- **April and November 2015** – We held a scientific committee meeting of the caribou project to plan fieldwork activities for the summer and fall 2015, and winter 2016.
- **Spring, Summer and Autumn 2015** – We presented our results on many occasions such as the 14th International Arctic Ungulate Conference (Røros, Norway), 83e congrès de l'ACFAS (Rimouski, QC Canada), the annual meeting of the Centre for northern studies (Quebec, Canada) Canada, the 40th Annual meeting of the Société Québécoise pour l'Étude Biologique du Comportement, the Arcticnet annual scientific meeting (Vancouver, BC Canada).
- **February and March 2016 –** Presentation of our research program, particularly the habitat experiment, to Kangiqsujuaq and Salluit communities.

RESULTS

Objective 1. Cumulative impacts of human disturbance on habitat selection and demography of migratory caribou (Ph.D. 1 – S. Plante)

We assessed caribou vulnerability to sport hunting for the Rivière-aux-Feuilles herd between 1997 and 2014. We used resource selection functions (Manly et al. 2002) to describe habitat selection patterns of 191 caribou and 65 sport hunters. We also characterized over 134 000 caribou harvest sites. We first found that habitat characteristics better explain the spatial distribution of caribou harvest than the habitat selection of caribou and hunters. Caribou were more vulnerable in proximity to roads and camps (Figure 1). Almost 83% of harvest sites were located within 10 km of a road. Caribou were, however, 11 times more susceptible to be harvested at only a few meters from a road than at 10 km from it. In comparison, caribou harvest was almost 14 times more likely to happen at only a few meters from an outfitter camp than at 10 km from it. Harvest sites were, however, spread on a larger area around outfitter camps than they were from roads, with 82% of the harvest happening within 60 km from a camp. Caribou were also more vulnerable on frozen lakes than in any other land cover types. We also found that caribou strongly avoided roads during the hunting season, whereas hunters strongly selected them. Outfitter camps were selected by both caribou and hunters. Other infrastructures, such as power lines and buildings, had no effect on caribou habitat selection, whereas hunters avoided buildings. Finally, caribou avoided lakes during the hunting season and hunters used them proportionally to their availability.

Objective 2. Spatiotemporal use of migration corridors by caribou (Postdoc – M. Leblond)

We assessed the responses of caribou to ice and water availability by studying their space use and movements on and around lakes and rivers. We used telemetry data collected between 2007 and 2014 on 96 migratory caribou from the Rivière-aux-Feuilles herd.

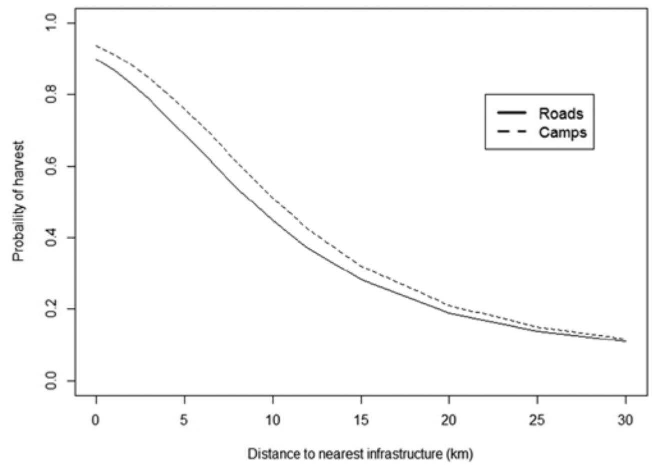

Figure 1. Probability of harvest for caribou of the Rivière-aux-Feuilles herd in relation to the distance to the nearest road or outfitter camp during the winter sport hunting seasons of 1997-2015, James Bay region, northern Québec, Canada.

We measured contemporary (digital MODIS maps updated every 8-days, 2000- 2014; National Snow & Ice Data Center: nsidc.org/) and historical (annual observations on Lake Nichicun, 1947-1985; Polar Data Catalogue: www.polardata.ca/) variations in freshwater ice availability and evaluated the concurrent responses of caribou to these changes using movement metrics (movement rate, turning angle) and step selection functions. Ice phenology on the largest water bodies in the caribou range did not change significantly between 2000 and 2014; however, a low-magnitude trend, similar to reported sea- and freshwater-ice declines across the Northern Hemisphere, was noticeable, i.e., thawing and freezing dates tended to occur at earlier and later dates, respectively. This trend correlated well with monthly values of North Atlantic and Arctic oscillations (i.e., breakup dates were related to the NAO in May whereas freeze dates were related to the NAO in October and the AO in September). Ice had a positive influence on caribou movement rates and directionality. For instance, the movement rates of caribou (corrected for individual and location frequency) were significantly higher on ice (1625 ± 51 m/h) and during detours (994 ± 31 m/h) than elsewhere in the study area (535 ± 2 m/h). Caribou selected ice and avoided water when moving across or in the vicinity of large water bodies. Interactions with water body type did not increase the goodness of fit, suggesting that caribou reacted similarly to large natural lakes, rivers, and reservoirs. When ice was unavailable, caribou rarely swam across (6% of crossings) and frequently circumvented water bodies for several km. Based on current climatic scenarios, it seems probable that caribou will face increasingly precocious melting and late freezing of lakes and rivers in their range, with potential consequences on the timing of their migrations and increased risks of drowning. Results of this study are now submitted:

- Leblond, M., M.-H. St-Laurent, and S. D. Côté. Submitted. Caribou, water, and ice – Fine-scale movements of a migratory Arctic ungulate in the context of climate change. Movement Ecology.

Objective 3. Evaluation of changes in space use of caribou using remote sensing (M.Sc. 1 – B. Campeau)

We assessed how the summer movement pathways adopted by collared caribou from the Rivière-George herd vary from year to year. They often originate in either the 1991-2000 or 2001-2011 core calving area and several recurring movement pathways can be identified for different time periods. Indeed, the same pathways are frequently adopted by the majority of collared caribou for several consecutive years. It is therefore possible to identify several distinct core summer areas, representing preferred movement pathways and foraging areas, based on changes in summer range use surrounding the shift in calving ground use post-2000 (Figure 2). Different core areas exist for the 1991-2000 and 2001-2011 time periods, but there are also certain hotspots, or areas of summer range overlap, which are consistently used during the whole 1991-2011 period of record (Figure 3).

As was the case for the Rivière-George calving grounds, the relationship between cNDVI (cumulative growing season NDVI) and growing season length can be modelled for the Rivière-George summer range using a simple power function (Figure 4). This model explains much of the observed variation in cNDVI in the global 1991-2011 Rivière-George summer range over the 1987-2011 period for which NDVI and climate data are available ($R^2 = 0.80$). The relationship between the ln-transformed values of cNDVI and growing season length is highly significant (d.f. = 1, F = 4058.9, P <0.0001). The residuals from the power function model can therefore be used to control for the influence of climatic variation on primary productivity, allowing for an investigation of other possible explanatory variables, chief among them being caribou foraging and trampling pressure. A positive linear relationship was also identified between cNDVI and average June-September temperature (d.f. = 1, F = 229.3, P <0.0001), but no significant relationship was identified between cNDVI and total June-September precipitation (d.f. = 1, F = 0.1, P = 0.7). In a multiple

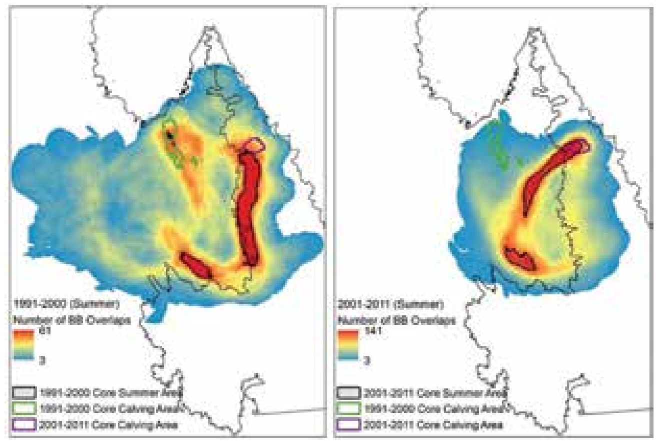

Figure 2. The distribution of the Rivière-George caribou herd in Northern Québec and Labrador during the summer period for 1991-2000 (left) and 2001-2011 (right), based on the annual Brownian Bridge (BB) 95% home ranges of all collared individuals (both males and females); the summer period was defined for each individual using First-Passage Time analysis; core areas were identified for each time period as those areas exhibiting a number of BB overlaps > 70% of the maximum number of overlaps for the time period; the 1991-2000 period includes home ranges from 147 caribou-years and uses a core area threshold of ≥ 43 BBs, whereas the 2001 to 2011 period includes home ranges from 194 caribou-years and uses a core area threshold of ≥ 99 BBs; note that areas with < 3 BB overlaps are excluded from the maps.

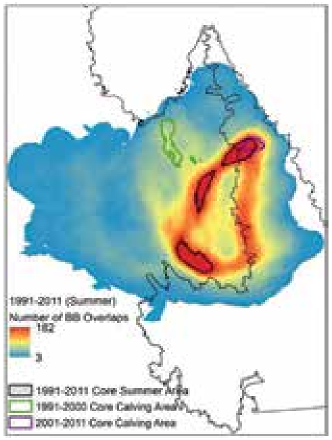

Figure 3. The distribution of the Rivière-George caribou herd in Northern Québec and Labrador during the summer period for 1991-2011, based on the annual Brownian Bridge (BB) 95% home ranges of all collared individuals (both males and females); the summer period was defined for each individual using First-Passage Time analysis; core areas were identified for each time period as those areas exhibiting a number of BB overlaps > 70% of the maximum number of overlaps for the time period; the 1991-2011 period includes home ranges from 341 caribou-years and uses a core area threshold of ≥ 128 BBs; note that areas with < 3 BB overlaps are excluded from the map.

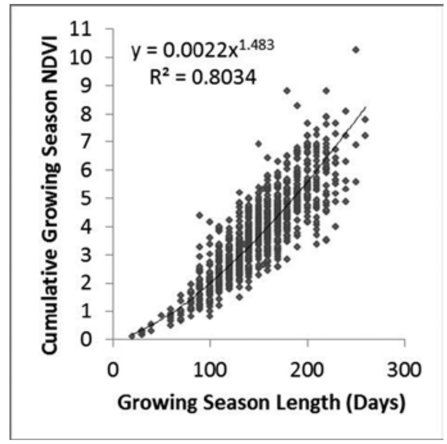

Figure 4. The power function used to model the relationship between cumulative growing season NDVI (cNDVI) and growing season length for the global 1991-2011 Rivière-George summer range; the points represent data from 1,000 1 km² AVHRR pixels that were randomly selected from the global summer range; 40 pixels were selected for each year of the 1987-2011 time period for which both AVHRR and climate data were available; cNDVI is determined based on the sum of all NDVI values that exceed 0.05, the threshold NDVI value used to define the growing season.

regression model including growing season length, average June-September temperature and total June-September precipitation as predictor variables for cNDVI (d.f. = 3, F = 885.2), all of the predictor variables were highly significant (P < 0.0001), but the model itself was a poorer predictor of cNDVI than the simple power function model described earlier (adjusted R^2 values of 0.72 and 0.80, respectively). AIC_c model selection demonstrated that the simple power function is the most parsimonious model. Positive temporal trends in cNDVI, growing season length and mean cNDVI-climate model residuals can be identified for the study area, defined by the minimum convex polygon (MCP) of all summer period caribou locations, for the 1991-2011 study period (Figure 5). A significant negative relationship (t = −2.44, P = 0.02) exists between the mean cNDVI-climate model residuals and RG herd population size for the global summer range MCP (Figure 6). However, no significant relationship was identified between these variables for the cores areas.

Objective 4. Determinants of annual caribou survival by age and sex (PhD 2 – B. Vuillaume)

This project only started in September 2015 and will allow us to identify the determinants of survival of migratory caribou from the Rivière-George and Rivière-aux-Feuilles herds for all sex-age classes. Ungulate survival rates may vary due to different parameters linked to habitat or demographic components such as sex ratio or recruitment (Gaillard et al. 2000). These fluctuations are related to the relative sensitivity of each age and sex classes to environmental determinants such as climate or vegetation productivity (Williams et al. 2002). To investigate survival in relation to environmental and demographic drivers, we started to analyze data from a satellite-marking program initiated in 1986, with more than 600 adult caribou of both sexes marked. Survival has been highly variable through time fluctuating with large-scale population trajectories. Yearling survival appears more affected by climate conditions than adult survival. We performed preliminary analyses for

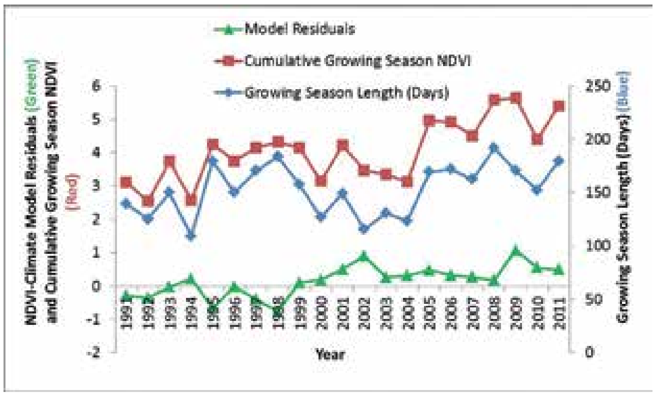

Figure 5. Temporal trends in NDVI-climate model residuals, cumulative growing season NDVI and growing season length for the Rivière-George caribou herd summer range MCP; a trend towards increased productivity and longer growing seasons is apparent for the study period.

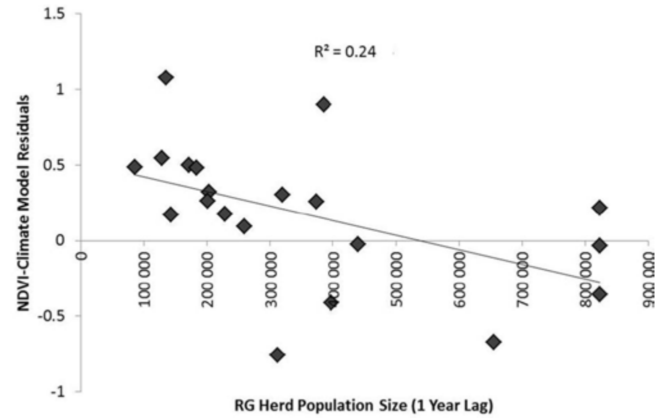

Figure 6. Model residuals vs. lag 1 year Rivière-George caribou herd population size for the summer range MCP; the negative relationship indicates that the model tends to overpredict NDVI at higher caribou densities, suggesting a negative influence of caribou foraging/trampling pressure on productivity.

the Rivière-aux-Feuilles herd for the period between November 2014 and October 2015. These results indicate an overall low survival rate and suggest a higher survival rate for adult females (0.83, SE = 0.08) than males (0.68, SE = 0.04). In addition to monitoring adult survival, we are launching a new study using camera collars fitted on adult females with a calf to study calf survival rate. Currently monitoring survival from birth to recruitment in the fall has never been conducted on individually-known migratory caribou.

Objective 5. Interactions between caribou and its predators (Ph.D. 3 – R. Rogers, Ph.D. 4 – M. Bonin)

We initiated a satellite monitoring program for wolves and black bears on the Rivière-George and Rivière-aux-Feuilles caribou herd ranges to measure the spatial overlap of caribou, wolves and bears, determine kill rates and assess temporal changes in the diet of both predators. Our goal is to maintain 20 collared wolves and 20 collared black bears on the range of each caribou herd. Ph.D. project 3 on space use of predators officially started in January 2016, but our preliminary results suggest migratory behavior of wolves from the range of the Rivière-aux-Feuilles caribou herd (Figure 7). Wolves do not appear to maintain annual territories but follow caribou in their migrations. Future work on wolf nutrition (see below) will allow us to better understand the role of caribou in the diet of these wolves and the utilisation of alternative preys. Wolves on the range of the Rivière-George caribou herd appear more sedentary in general, and some packs never overlap with the caribou range (Figure 8). It is clear from their movement tracks that packs that overlap with caribou have much greater movement rates than those that do not overlap with caribou. Recent fieldwork revealed a low abundance of wolves on the Rivière-George herd range, most likely indicating a numerical response of wolves following the 98% reduction in the abundance of the Rivière-George caribou herd. However, black bears are abundant, especially around the caribou calving grounds.

To reconstruct the diets of wolves and black bears, we will use a combination of methodological approaches: scat analyses (Floyd et al. 1978, Mattioli et al. 2011), stomach content (Pezzo et al. 2003), stable isotopes (Milakovic and Parker 2011; Milakovic and Parker 2013) and DNA barcoding (Pompanon et al. 2012). By combining these approaches, we will be able to evaluate the diet composition of each predator at different time scales and achieve a high taxonomic resolution for the consumed prey items. Ph.D. project

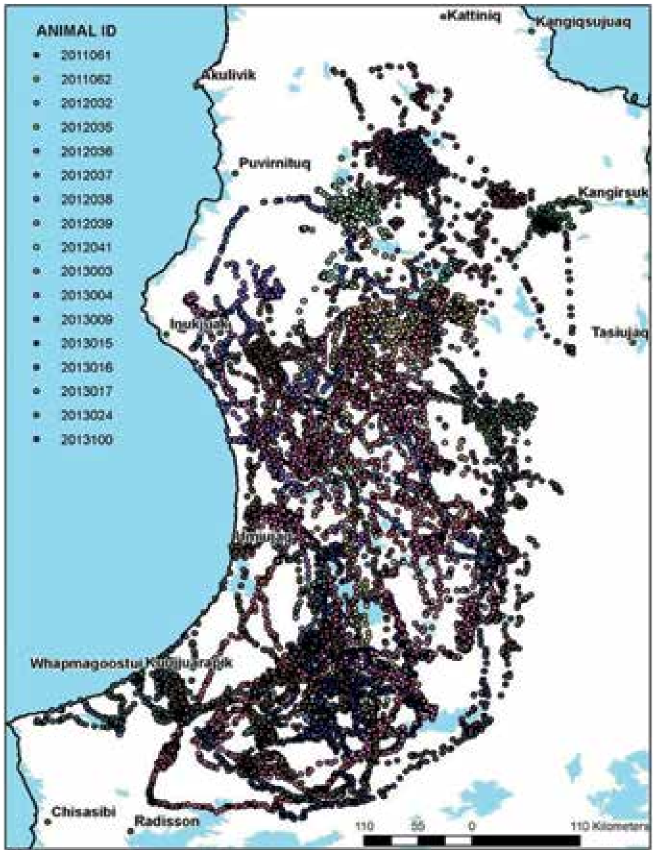

Figure 7. Locations of satellite-collared wolves on the range of the Rivière-aux-Feuilles caribou herd between June 2011 and December 2015.

4 started in September 2015. Since then, we have focused on the collection of samples of predator tissues (i.e. hair, muscles and blood; Table 1) and potential prey for the analysis of stable isotopes. We have also collected digestive tracts of wolves and are working on the development of a recovery program of predator carcasses in collaboration with native peoples of Eyou Istchee, Nunavik, and Nunatsiavut.

Objective 6. Indirect consequences of the intensification of the shrub layer on summer food resources of caribou: influence of snow and light attenuation (M.Sc. 2 – to be determined)

In July 2015, we implemented an experiment simulating snow interception and shading of ground

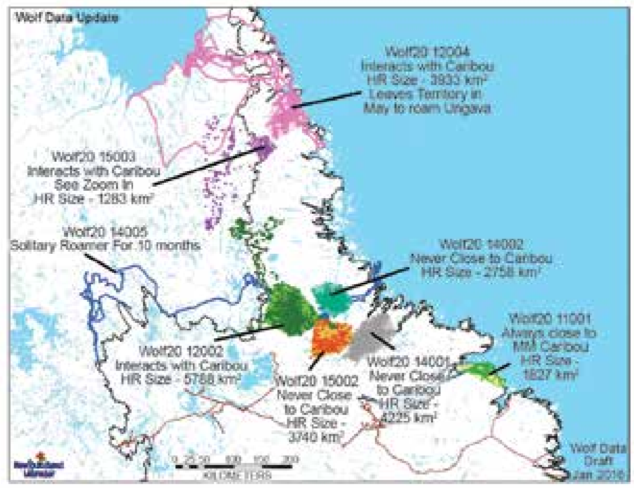

Figure 8. Locations and home ranges of satellite-collared wolves on the range of the Rivière-George caribou herd between June 2011 and January 2016.

layer vegetation by erected shrubs. The experiment will be conducted over four years at Deception Bay, Nunavik, within the summer range of the Rivière-aux-Feuilles caribou herd. The design is composed of nine blocks separated in two main plots receiving one out of two levels of the snow depth treatment. A first 3 x 6 m plot is located 6 m downwind from a 1 m high and 9 m long snow fence (Figure 9) while the control is located at least 6 m to the side and in front of the snow fence. The objective is to increase the snow depth in the treated exclosures to approximately 75 cm (Semenchuk 2013). These plots are enclosed in 1.2 m high wire fences to exclude caribou (Figure 9). Beginning in spring 2016, we will apply a two level shading treatment using a shading tarp (Hansen et al. 2006; sunblocker®) in a 3 x 3 m subplot in each exclosure. The 36 plots of the experiments were equipped with soil temperature sensors (Hobo Pendant Data logger). We also equipped one block with sensors for soil moisture (Decagon EC-5) and plot-level Normalized Differences Vegetation Index (NDVI; Decagon SRS) to test the feasibility of remote monitoring. Finally, we estimated the biomass and composition of the plant community in each plot using the point intercept method (Goodall 1953) and we harvested foliar tissues from *Betula glandulosa*,

Table 1. Sample sizes for predator tissues harvested in the ranges of the Rivière-aux-Feuilles (RAF) and Rivière-George (RG) caribou herds.

Predator	Caribou herd	Hair	Muscle	Blood
Gray wolf	RAF	16	19	10
	RG	1	1	0
Black bear	RAF	7	7	5
	RG	38	26	36

Figure 9. An exclosure located downwind from one out of nine snow fences erected at Deception Bay, Nunavik, in July 2015 to simulate the indirect effects of the development of the shrub layer on snow interception and shading of ground layer plants (shading tarp not installed on this picture). A second exclosure without a snow fence is also present at each experimental site (not visible on the picture).

grasses and *Carex* spp. to conduct analyses of their chemical composition.

DISCUSSION

Objective 1. Cumulative impacts of human disturbance on habitat selection and demography of migratory caribou (Ph.D. 1 – S. Plante)

In ungulates, human disturbance can lead to a loss of habitat, change behavioral patterns and habitat selection (Seip et al. 2007), upset predator-prey relationships and change life-history parameters (Leblond et al. 2013). Moreover, anthropogenic and natural disturbances can have cumulative effects (National Research Council 2003). While negative effects of human disturbance on caribou demography have been documented, the link between selection of disturbed habitats and survival remains to be verified. In this perspective, it is crucial to evaluate the impact of all human disturbances, especially those that can cause direct mortality such as sport hunting.

Our results suggest a spatial dissociation between use by caribou and hunters, and harvest distribution. This dissociation was also reported for elephants (*Loxodonta africana*) and woodland caribou (James and Stuart-Smith 2000, Roever et al. 2013). This may be explained by the observation that caribou were more vulnerable where habitat characteristics were either generally avoided by caribou or hunters or not selected by both. We found that proximity to hunting infrastructures, such as roads and outfitter camps, had a tremendous impact on caribou vulnerability. We know that accessibility to the hunting territory, via roads and camps, influences both habitat selection by hunters and harvest distribution (Brøseth and Pedersen 2000, Diefenbach et al. 2005, Lebel et al. 2012). High hunting pressure near camps, for example, can lead to higher probability of harvest (Brøseth and Pedersen 2000). In addition, vulnerability of game species is known to be higher in open fields or fragmented areas, where visibility and detectability by hunters are good (Foster et al. 1997, Lebel et al. 2012, Norum et al. 2015). We found that lakes were risky for caribou during the hunting season. Our results also suggest that caribou may favor safety during the hunting season by avoiding risky areas such as roads and lakes. Further development in northern ecosystems could expand the territory available to hunters and increase vulnerability of Arctic species to hunting. We thus recommend future studies on cumulative impacts to consider roads not only as a human disturbance causing avoidance, but also as a potential source of mortality due to the increase in accessibility for human predators (James and Stuart-Smith 2000, Trombulak and Frissell 2000). The next step is to evaluate cumulative impacts of various sources of human disturbances, including sport hunting, on caribou habitat selection.

Objective 2. Spatiotemporal use of migration corridors by caribou (Postdoc – M. Leblond)

Identification and protection of migratory routes is a major issue in the conservation of migratory ungulates (Berger 2004, Sawyer and Kauffman 2011). Caribou perform one of the most impressive terrestrial long-distance migrations in the world (Berger 2004). In Northern Québec (Canada), caribou travel distances up to 1000 km from their calving grounds in the Ungava Peninsula to their wintering areas in the boreal forest. Along the way, they encounter many lakes and rivers, which are highly abundant in the region. Freshwater lakes and rivers of the Northern Hemisphere have been freezing increasingly later and thawing increasingly earlier during the last century (Magnuson et al. 2000). We demonstrated that climate change, through variations in ice availability and phenology, influenced the movements of migratory caribou. We also know from an ongoing research (M. Le Corre, C. Dussault, and S. D. Côté, unpublished observations) that caribou in Northern Québec are initiating their spring and fall migrations earlier, possibly in response to the changing environment. This response may allow caribou to avoid a potential mismatch between the timing of migration and freshwater ice availability. With a warming Arctic, and assuming caribou are unable to adjust the timing of their migrations further (Post and Forchhammer 2008), caribou may encounter unfrozen lakes more frequently. This could force caribou to cross water bodies more frequently in open water, causing increased risks of drowning (Miller and Gunn 1986). It could also lead caribou to circumvent water bodies for several kilometres, with possible negative consequences on energy reserves, body condition, and reproductive success. The long-term conservation of wide-ranging species will ultimately depend on our ability to identify the fine-scale behavioural reactions of individuals to broad-scale changes in climate and land use.

Objective 3. Evaluation of changes in space use of caribou using remote sensing (M.Sc. 1 – B. Campeau)

The Rivière-George caribou herd has demonstrated a decrease in the size of its summer range and a change in preferred summer movement pathways over the 1991-2011 period for which reliable satellite telemetry data are available. These changes, like the changes in calving ground use, appear to reflect the demographic trends of the herd and may be related to changes in green forage availability. The summer range and movement pathways are also directly influenced by the location of the calving grounds, since they represent the starting point of the summer movement period for non-barren adult females. The changes in summer range use can therefore be examined in relation to the post-2000 eastward shift in calving grounds use.

A trend towards higher primary productivity is apparent for the global 1991-2011 Rivière-George herd summer range and for the core summer areas. This trend may reflect both the increase in growing season length in these areas and the decrease in caribou foraging/trampling pressure associated with the Rivière-George herd population decline. However, the extremely close association between growing season length and cNDVI suggests that climatic variation is primarily responsible for the observed changes in productivity.

The positive trend apparent for the cNDVI-climate model residuals over the 1991-2011 period indicates that the cNDVI-climate model tends to overpredict range productivity in the earlier years of the study period, when caribou were abundant, but tends to underpredict range productivity in the latter years of the study period, when caribou were less abundant. This trend appears to demonstrate an effect of caribou/foraging trampling pressure on range productivity. Caribou foraging/trampling pressure was presumably highest in the study area during the early portion of the study period, perhaps reducing range productivity relative to that predicted by the cNDVI-climate model, resulting in the predominately negative model residuals. The decrease in caribou foraging/trampling pressure in the latter portion of the study period may have allowed for vegetation recovery and an increase in range productivity beyond that predicted by the cNDVI-climate model, resulting in the predominately positive model residuals.

The significant negative relationship between the cNDVI-climate model residuals and RG herd population size for the summer range MCP suggests that primary productivity may be reduced at high caribou density, but this relationship was not apparent for the core areas, where one would expect the most intense caribou foraging/trampling pressure. This result suggests that the core areas identified in our analyses do not necessarily represent areas of intense caribou summer use. It may also suggest that our methodology used to estimate caribou density, relying on a small number of collared caribou, is insufficient to assess inter-annual variation in core area caribou density.

Summer forage limitation likely contributed to the Rivière-George herd population decline, but our lack of reliable caribou location and population size data pre-1991, during the period of population growth, restricts our ability to identify habitat deterioration associated with caribou foraging/trampling effects. We observed an increase in range productivity during the 1991-2011 period of caribou population decline, but this positive trend in range productivity is largely explained by changes in growing season length. However, deviations from the productivity-climate relationship (i.e. our cNDVI-climate model residuals) appear to be related to caribou density; mean model residuals in the global summer range MCP were negatively correlated with estimates of caribou abundance on the summer range, suggesting that caribou foraging/trampling has a negative influence on overall productivity.

Other changes in habitat that cannot be detected in our analyses, such as changes in vegetation community composition, may allow for habitat deterioration without directional change in overall productivity. Earlier work has demonstrated that caribou foraging/trampling pressure can reduce the abundance of preferred forage species in favor of less palatable species (Manseau et al. 1996). Increases in range productivity, as measured with NDVI or other remotely-sensed indices, may not necessarily represent increases in forage abundance for caribou. A focus on range productivity can also overlook potential changes in forage accessibility (e.g. relating to shrub height and density) and nutritional quality (e.g. C:N ratios of plant tissue) that also influence caribou habitat suitability. Remote sensing studies need to be complemented by field-based studies to fully evaluate habitat change.

Objective 4. Determinants of annual caribou survival by age and sex (PhD 2 – B. Vuillaume)

Ungulate survival rates may vary according to various individual characteristics but also due to different parameters linked to habitat or demographic components such as sex ratio or recruitment (Gaillard et al. 2000). These fluctuations are related to the relative sensitivity of each age and sex classes to environmental determinants such as climate or vegetation productivity (Williams et al. 2002). Sensitivity analyses comparing survival and fecundity estimates among age and sex classes indicate that adult female survival has the greatest potential to influence changes in population size (i.e. the greatest elasticity), and suggest that harvesting adult females can have strong impacts on population dynamics (Gaillard et al. 1998, Hamel et al. 2006). Because of this, this is essential to assess survival rates of both sexes in caribou. The current survival rates of migratory caribou are low and indicate population declines for both herds. The next steps will be to identify the factors explaining variations in survival rates in both sexes, and determining whether mortality due to hunting is additive or compensatory.

Objective 5. Interactions between caribou and its predators (Ph.D. 3 – M. Bonin, Ph.D. 4 – R. Rogers)

Migratory caribou in Northern Quebec and Labrador currently experience low survival and very few calves survive to October, suggesting a high juvenile mortality despite a recent improvement in body condition of adult females, at least for the Rivière-George herd (Taillon et al. 2012). Increased predation could explain this apparent contradiction. Wolves are the main predator of caribou (Kuyt 1972), but black bears can also take many fawns (Wittmer et al. 2005, Pinard et al. 2012). Based on field observations and data from our satellite-monitoring program of predators, we have observed high predation rates in the spring around the calving period of caribou as well as during winter when caribou are concentrated in lichen-rich habitats and snow impede their movements. Because we have identified calving as a critical period for caribou, we will examine the contribution of caribou as a food resource around that particular period. Tissues and scat samples of predators will be collected before and after the calving period of caribou to examine whether neonates could act as a pulsed food item (Bastille-Rousseau et al. 2011). We will also examine the contribution of caribou in the diet of wolves and black bears on an annual and seasonal basis. One next step is also to assess the spatial and temporal co-occurrence of caribou and its predators based on step selection functions. Our goal is to produce maps of predation risk and contrast them to observed caribou space use to understand the role of predation in migratory caribou habitat selection.

Objective 6. Indirect consequences of the intensification of the shrub layer on summer food resources of caribou: influence of snow and light attenuation (M.Sc. 2 – to be determined)

A striking consequence of global warming is the densification of the shrub layer in the subarctic (Myers-Smith et al. 2011, Naito and Cairns 2011). The snow-shrub hypothesis (Sturm et al. 2001, Myers-Smith et al. 2011) proposes that erect shrubs increase the thickness of snow cover (Myers-Smith and Hik 2013) insulating the soil (Nobrega and Grogan 2007, Myers-Smith and Hik 2013), thus promoting microbial activity (Nobrega and Grogan 2007). These conditions could improve shrub growth by increasing the availability of nutrients (Vankoughnett and Grogan 2014). Ground temperature during the snow free period, however, may be reduced by shading under shrubs (Myers-Smith and Hik 2013). The effects of these changes on plant quantity (Rumpf et al. 2014) and quality (Semenchuk et al. 2015) are expected to be contrasted across species, confusing the prediction of their effects on food resources for caribou. Our experiment will allow to determine the effects of increased snow cover and light attenuation by shrubs on the quality and quantity of forage for caribou in summer.

The implementation of this simulation experiment involves ongoing methodological development both for the application of treatments and continuous remote monitoring of plots. We will visit the experimental sites during winter 2016 to measure the accumulation of snow within the exclosures located downwind of the snow fences and assess the efficiency of the NDVI and soil humidity sensors. We may move the snow fence closer or further from the exclosures to fine tune the simulation of an homogeneous snow depth of approximately 75 cm in treated plots. If the sensors performed as expected, we will install additional soil moisture and NDVI sensors in early June 2016, at the same time as we will recover data from temperature sensors and stretch shading tarps over half of the enclosures following a design we experimented in fall-winter 2015-16. We will return in July to estimate the biomass of the vegetation in the plots and to harvest plant material. We will also conduct chemical analyses of the foliar contents (nitrogen, carbon, fibers, terpenes) of selected forage plant species, and develop partial least-square regressions with the near-infrared spectrum of the samples to increase the efficiency of the monitoring of the quality of forage in the coming years. We plan to recruit an MSc student in spring 2016 and follow the experiment until 2018.

CONCLUSION

Caribou are an extremely important part of the ecology, economy and culture of the Arctic, and most Arctic herds are currently declining (Vors and Boyce 2009). In some cases, for example for Peary caribou in the High Arctic, global warming appears directly responsible for drastic declines and local extirpations (Tews et al. 2007). In other cases, it has been hypothesized that climate change and anthropogenic disturbance may be responsible for caribou declines, but still little scientific evidence is available. With their high mineral potential, northern Quebec and Labrador are likely to see a major increase in industrial activities in the near future. These developments could have significant ecological and demographic impacts on caribou. Our research addresses a fundamental need of conservation in the Arctic by examining the factors affecting space use and population dynamics of migratory caribou. Our work will provide crucial information on the cumulative impacts of climate change and anthropogenic disturbance, including hunting, on caribou population size. It will also allow predictions of further range use and population size of caribou that will be crucial to maintain sustainable subsistence and sport hunting.

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Biology of the Three Morphotypes of Arctic Char in the Nettilling Lake System: Developing Sustainable Commercial and Subsistence Fisheries in Nunavut's Two Largest Lakes

Project Leader

Aaron Fisk (University of Windsor)

Collaborators

Daniel Heath (University of Windsor)
Janelle Kennedy (Fisheries and Sealing Division, Department of Environment)
Ross Tallman (Fisheries and Oceans Canada - Freshwater Institute)
Angela Young (Government of Nunavut - Fishing and Sealing Division)

ABSTRACT

In 2013 Expedition Q – a group crossing Baffin Island using traditional sea kayaks – discovered a previously unknown arctic char migration on the Amadjuak River which flows from Amadjuak Lake into Nettilling Lake to the North. Nettilling Lake is the biggest lake in the Eastern arctic and is the sixth largest lake in Canada. It is has both sea-run and resident char within its waters. The subpopulation of sea run char is estimated to be the largest in Nunavut; no estimates of the resident char population have ever been made. Nettilling Lake also has the largest commercial quota in Nunavut, none of which is being harvested due to a lack of economic viability. The discovery that substantial numbers of char migrate south enriches our knowledge of this ecosystem, and raises the possibility that a viable winter fishery could be established that would supply the currently underserved Iqaluit market. Every summer from 2015-17 an Iqaluit-led expedition is being mounted to gather biological samples of the char in the river. The team will also tag arctic char, and their movements up and down the river will be recorded by monitors moored at key choke points throughout the river. Every winter a second expedition will be mounted to explore the many small frozen lakes along the southern shore of Amadjuak Lake to look for and tag char at their furthest point of migration – which also happens to be the closest point to char-hungry Iqaluit. The results from this project will inform future efforts to understand and sustainably manage the Amadjuak and Nettilling Lake winter fisheries.

KEY MESSAGES

- First year of fieldwork was a complete success for the “Biology of the three morphotypes of Arctic charr in the Nettilling Lake system: Developing sustainable commercial and subsistence fisheries in Nunavut’s two largest lakes”.
- All 12 acoustic receivers deployed in August 2014 were recovered and data downloaded in August 2015, all were re-deployed along with five planned recovers at the mouth of the Koudjuak River.
- More than half of the 42 tagged charr in 2014 were detected on receivers. An additional 60 charr were tagged in August 2015. All of these tags have a four year life span.
- A total of 227 fish were sampled, 60 were released alive tagged (fin clip taken) and 147 were euthanized and sampled for fin, liver, gill and muscle for stable isotope analysis. All euthanized fish had a full morphometric analysis.

OBJECTIVES

This project has three major objectives:

Objective 1 – *Collect basic biological data and archive samples.* Given the lack data of data or samples from this unique system, (no sampling undertaken between 1977 and 2014), there is a need to collect basic information (length, weight, structures for age determination (otoliths), sex, state of sexual maturity, fecundity, colour, parasite loads, and tissue samples) on the Arctic Charr. In addition to the food web ecology objective below, we will endeavour to find additional financial resources for future genetics studies.

Objective 2 – *Understanding the feeding ecology of Nettilling/Amadjuak system Arctic Char*. Given the unique prey base in this system and the different morphotypes we will measure stable isotopes in liver and muscle tissues of the three Arctic Charr morphs collected in the two large lakes and the river (and biopsies of tagged fish). Turnover rates of stable isotopes are faster in liver and give a more recent evaluation of feeding (3-6 months), whereas muscle integrates diet over 6-12 months. Prey samples will also be sampled to estimate char diet using Bayesian based mixing models (Parnell et al. 2013), and isotopic niche widths will be used to examine potential competition for resources.

Objective 3 – *Determine the timing, extent and dynamics of the movements and migration of char in the Nettilling/Amadjuak system.* Complementing the basic biological information and feeding ecology, data on the movements of tagged individual char will provide key insights into specific behavioural strategies of the morphotypes, and will contribute towards an understanding of the population dynamics and interplay between anadromous and non-anadromous char. From the community and fishery perspective, if the spring migration consists of high densities of fish and is predictable with respect to key observable environmental variables (for ex. the lunar cycle), then a spring char harvest on the Amadjuak River could be a viable strategy to improve local food security. A proper model of the migration of char in both systems, the maximum extent of migration of harvestable char and the degree of connectedness of char stocks between the two lakes is critical for formal assessment by DFO under the precautionary approach to management. Finding char in the lakes near the southern shores of Amadjuak Lake would immediately improve the outlook for the winter subsistence and commercial char harvest serving Iqaluit, and tagging individual char would provide key insights into the behavior of this migratory subpopulation

INTRODUCTION

The Arctic Char (*Salvelinus alpinus*) is the most harvested species of wildlife in Nunavut (Priest and Usher 2004), represents a culturally important species and is used by Inuit across the territory for both subsistence and commercial purposes. The Federal Government and the Government of Nunavut have both identified the development of commercial fisheries for anadromous (i.e., searun) Arctic Char as a priority because it provides a sustainable and culturally meaningful opportunity for economic development (Government of Nunavut and NTI 2005; Rompkey and Patterson 2010). Commercial fishing for Arctic char currently generates approximately $1.4 million annually and employs a large percentage of Nunavumiut both seasonally and permanently in most communities (Government of Nunavut and NTI 2005). Within the Canadian Territories the current demand exceeds the available supply by approximately threefold. By numbers Char is the most harvested animal in Nunavut and every community utilizes Arctic Char.

Nettilling Lake, the largest lake in Nunavut and the largest found on an island in the world, has the largest commercial char quota in the Eastern Arctic at 22,700 kg (Kristofferson et al. 1991). The Nettilling Lake fishery has been dormant since at least 2001 due to the high cost of air transportation of harvested char back to Iqaluit by Twin Otter airplanes (Janelle Kennedy, personal communication). Nettilling Lake is connected to the ocean (Foxe Basin) to the west by the Koukdjouak River, and to the large Amadjuak Lake to the south via the Amadjuak River. Amadjuak Lake has its own charr quota of 9,100 kg, but this quota has never been active because the char population is considered to be landlocked and thus vulnerable to exploitation. It is also thought to be of lesser value due to high parasite loads (Popko 1980, Kristofferson et al. 1991). In August of 2013 and 2014, previously unknown Arctic Char migrations were documented in the Amadjuak River and the north end of Amadjuak lake that included all three known morphs (landlock, anadromous green and anadromous silver) (William Hyndman, unpublished data). This strongly suggests that anadromous char may be present in Amadjuak Lake opening the possibility of a fishery that is closer to Iqaluit and consequently more economically viable. Amadjuak is close enough to Iqaluit for a viable winter subsistence or commercial ice-fishery, and even southern Nettilling Lake could be a possible fishery if the catches of char were reliable. These findings also support the development of a recreational or charter-based summer fishery.

In addition to the obvious fishery opportunities that Lake Nettilling/Amadjuak offers, there are many unanswered questions over the general biology and ecology of Arctic Charr in this unique freshwater system, particularly relating to the different morphotypes. Lake Nettilling is 111 X 97 km across, making it the 6th largest lake in Canada. The lake has a maximum depth of 132 m and ~74% of the lake is deeper than 20 m with a west region that is deeper with few islands and a shallower region to the east that has numerous islands of various sizes (Oliver 1964). Ice starts to break up in July, mainly at the river mouths with surface temperatures > 7 ^oC in August. The ice reforms in late September and early October, with ice varying in depth between 1.5 and 1.9 m at its maximum (Oliver 1964). In addition to char, the lake supports populations of threespine (*Gasterosteus aculeatus*) and ninespine (*Pungitius pungitius*) stickleback fish and significant numbers of ringed seal (*Pusa hispida*). Interestingly, the lake supports large populations of Chironomid larvae populations of other invertebrates (e.g., amphipods and molluscs) are much smaller. This contrasts most arctic lakes in the region where invertebrates are typically much more abundant than Chironomids (Oliver 1964). The unique diversity of potential prey in Lake Nettilling may represent an atypical diet for these Arctic Charr, which could explain proposed higher growth rates of both anadromous and non-anadromous morphotypes in this system (Kristofferson et al. 1991). Given the two colours of anadromous morphotypes, questions remain about the relative importance of lake resources and whether the potentially large food base of this lake explains the abundance of the different morphs. Given this, we hypothesize that the anadromous "green/red" morphotypes (anadromous char were easily identified by smaller heads and bigger bodies), that have similar colouration to the landlock morhotypes, have a greater reliance on lake production than silver morphotypes.

Despite their cultural and commercial importance, relatively little is known about the marine and freshwater migrations of Arctic char for any system (Roux et al. 2011). Anadromous Arctic Charr migrate to the marine environment during ice breakup to feed, before returning to the freshwater in the fall to spawn. There exists a wide range of possible movement and migration strategies of Arctic Charr in the Nettilling/Amadjuak system given the complexity of, the ecosystem that includes a number of rivers, two large lakes, and potentially numerous smaller lakes. As well, recent acoustic telemetry work in Cambridge Bay, has questioned the paradigm of this distinct marine/freshwater finding that searun Arctic Charr can make numerous movements into freshwater during their marine phase, and these can include movements into systems that are not natal (Jean Sebastian Moore, unpublished data).

Given the colour types in the two anadromous morphs, could silver individuals spend more time at sea? Do the three morphotypes have variable movement behaviors in the system and/or do they choose unique spawning locations? Given the lack of basic information on these Arctic Charr populations, a first step to ensure sustainable harvesting if fisheries developed is to understand their large-scale movements patterns. This would include the times fish leave and return from the ocean and the times of movement within winter residency locations between the two large lakes and numerous lakes of the Amadjuak River.

In August of 2014 an exploratory trip to the Nettilling/Amadjuak system was undertaken to initiate studies on the movement, feeding ecology of these Arctic Charr morphs. This highly successful field expedition deployed a preliminary acoustic telemetry array in the Amadjuak River, the north end of Amadjuak Lake and the south end of Nettilling Lake, surgically implanted acoustic transmitters (also called tags, Vemco V13 1L and V16 4H) in 42 Arctic Charr of all three morphotypes as they migrated up the Amadjuak River, and took fin clippings from 45 individuals for stable isotope and genetics analyses. The acoustic tags produce a tag specific communication that is recorded when within range of an acoustic receiver (~ 1 km). The tags were programmed to communicate approximately every three minutes for up to four years (duration of this proposed project). The receiver array, deployed for a full year (to be collected in August 2015), was designed to determine how far up the river the tagged fish travel, if they progressed to Amadjuak Lake, and when/if the fish return to Nettilling Lake.

This proposal seeks to return to the Amadjuak River in each of the next three summers (2015-2017) to download, service, maintain and redeploy the acoustic monitor array and importantly to expand its spatial scope and increase the number of tagged fish in the system. We will also collect more tissue samples (include potential prey samples and biopsies from tagged fish) for stable isotope analysis to examine intra and inter-specific feeding behaviours among morphs. Thus, we will apply a multidisciplinary approach integrating traditional knowledge of the area with acoustic telemetry and feeding ecology using stable isotopes. Our study will address key challenges in the future management of this fishery, provide crucial information on critical freshwater and marine habitats, and establish a basis for understanding the ecological factors that will be most important in predicting the response of Arctic Charr to a changing Arctic. These goals align with the ArcticNet target research goals #5 Impacts of climate shifts on marine and terrestrial ecosystems and their services and #11 Food and water security in northern communities.

ACTIVITIES

The August 2015 field season was a complete success. Two trips were made to the Lake Nettilling and Lake Amadjuak system:

1. Trip 1: Three team members from the Government of Nunavut travelled by Twin Otter to the Environment Canada Field station near Koudjuak River. Using donated helicopter time, the team survived the mouth of the Koudjuak River in Nettilling Lake for appropriate location to place five acoustic moorings. The helicopter then moved a small boat to the area and waited while the receivers were deployed. These receivers will provide information on which tagged charr move to the ocean.
2. Trip 2: Was a 12 day rafting trip from Lake Amadjuak to Lake Nettilling by a team of six people (five employed by the Government of Nunavut and one employed by University of Windsor), brought and retrived by Twin Otter flights from Iqaluit (covered by PCSP funds). This group retrieved the 12 moorings from 2014, downloaded the data and re-deployed the receivers. A total of 227 fish were sampled, 60 were released alive tagged (fin clip taken) and 147 were euthanized and sampled for fin, liver, gill and muscle for stable isotope analysis. All euthanized fish had a full morphometric analysis.

Tissues samples have been shipped to the University of Windsor for stable isotope analysis, which have begun (expected completion date April 2016). Tissues have also been provided for a genetic analysis of the three different morphs.

Telemetry data is currently being analyzed to eliminate false detections. Range test data for the telemetry is also being assessed. This analysis will be completed by April 2016 and will provide insights on the position of moorings and possible movement to new locations.

RESULTS

A total of 227 fish of all three morphs were caught and sampled, 60 were released with an acoustic tag. All receivers were recovered in good condition and redeployed, along with five addition receivers deployed to catch fish moving to the ocean. At least 22 Arctic Charr tagged in 2014 were detected by the receivers. Morphometric, stable isotope and telemetry data is now being analyzed. As this is the first year of the project, there are no results to report yet.

DISCUSSION

Year 1 of this project brought exciting results. All 12 receivers deployed in August 2014 were recovered in August 2015, a one year deployment. Given the high flow and unknown ice characteristics of this system this is a remarkable achievement given the receivers were deployed at depth for 12 months. Of note, this is the first use of a new Vemco acoustic receiver with a built-in acoustic release. These built-in receivers save space, weight and money. The fact they worked so well opens up new opportunities for research in remote hostile places.

We were also encouraged by the high number of fish detected. Although assessment of this data is very preliminary, it does build well for future work and with more tagged fish in the system.

CONCLUSION

Acoustic telemetry is a vital technique for studying the movement of remote Arctic Charr lake and river populations.

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Monitoring and Managing Muskox Health for Food Security and Ecosystem and Socio-Economic Resilience: Integrating Traditional, Local, and Scientific Knowledge

Project Leader

Susan Kutz (University of Calgary)

Network Investigators

Sylvia Checkley (University of Calgary)
Christopher Kyle (Trent University)
Peter Molnar (University of Alberta)
Maribeth Murray (Arctic Institute of North America)
Frank van der Meer (University of Calgary)
Katherine Wynne-Edwards (University of Calgary)

Collaborators

Jan Adamczewski (Government of the Northwest Territories)
Layne Adams (U.S. Geological Survey (USGS) Alaska Science Center)
Morgan Anderson (Government of Nunavut)
Kimberlee Beckmen (USGS Alaska Sience Center)
Roman Biek (University of Glasgow)
Shane Black (Canada North Outfitting)
Marsha Branigan (Government of the Northwest Territories)
Joe Cook (University of New Mexico)
Steeve Côté (Université Laval)
Tracy Davison (Government of the Northwest Territories)
Bert Dean (Nunavut Tunngavik Incorporated)
Andrew Dobson (Princeton University)
Mathieu Dumond (Government of Nunavut)
Brett Elkin (Government of the Northwest Territories)
Craig Gerlach (University of Calgary)
Eric Hoberg (USDA Agriculture Research Service)
Wendy Hutchins (University of Calgary)
Claire Jardine (University of Guelph)
Myles Lamont (Government of Nunavut)
Lisa-Marie Leclerc (Government of Nunavut)
Manigandan Lejeune (University of Calgary)
Donald McLennan (Aboriginal Affairs and Northern Development Canada)
Karin Orsel (University of Calgary)
Peter Peller (University of Calgary)
Shane Sather (Government of Nunavut)
John Sauro (Canada North Outfitting)
Craig Stephen (University of Saskatchewan - Canadian Wildlife Health Cooperative)
Lilian Tran (University of Waterloo)
Morten Tryland (University of Tromso)
Ruth Zadoks (University of Glasgow)

HQP

Alejandro Aleuy, Doctoral Student (University of Calgary)
Chimone Dalton, Doctoral Student (University of Calgary)
Pratap Kafle, Doctoral Student (University of Calgary)
Angeline McIntyre, Doctoral Student (University of Calgary)
Alexander Nascou, Doctoral Student (University of Toronto)
Matilde Tomaselli, Doctoral Student (University of Calgary)
Maya Bastille, Masters Student (Stiftung Tierärztliche Hochschule Hannover)
Donavan Jackson, Masters Student (University of New Mexico)
Dianna Krejsa, Masters Student (University of New Mexico)
Erin Prewar, Masters Student (Trent University)
Josh Sullivan, Masters Student (University of Calgary)
Anja Carlsson, Post-Doctoral Fellow (University of Calgary)
Bryan Macbeth, Post-Doctoral Fellow (University of Calgary)
Nora Novarro-Gonzalez, Post-Doctoral Fellow (University of California, Davis)
Bindu Panikkar, Post-Doctoral Fellow (University of Calgary)
Katelyn Jackson, Technical Staff (Trent University)
Felix Nwosu, Technical Staff (University of Calgary)
Angie Schneider, Technical Staff (University of Calgary)
Jian Wang, Technical Staff (University of Calgary)
Ruokun Zhou, Technical Staff (University of Calgary)
Sarah Grond, Undergraduate Student (University of Calgary)
Sean Lang, Undergraduate Student (University of Guelph)
Brianne Morgan, Undergraduate Student (Trent University)
Jessica Phillips, Undergraduate Student (University of Toronto)
Breanna Taylor, Undergraduate Student (Trent University)

Northern HQP

Cathy Anablak, Northern Student (Nunavut Arctic College)
Ali Pederson, Northern Student (Nunavut Arctic College)
Leonard Wingnek, Northern Student (Nunavut Arctic College)

ABSTRACT

Muskoxen are integral to the culture, food system, economy, and ecosystem health in the Arctic. In recent years, widespread mortalities of muskoxen on Victoria and Banks Islands, with concomitant population declines, have raised concerns about the health and sustainability of these animals. Additionally, sick and declining muskox populations will increase the already substantial food insecurity concerns across the Canadian North. Our work aims to (i) determine the current health status of muskoxen in increasing and decreasing populations of muskoxen in the Inuvialuit Settlement Region and Kitikmeot region, (ii) evaluate the factors which influence health, including disease, contaminants, climate, disturbance, and stress in these differing populations, (iii) investigate the ecology of muskox diseases, including three recently emerging diseases, through scientific study and examination of Traditional Ecological Knowledge and Local Expert Knowledge, (iv) develop key indicators of health that can be incorporated into muskox monitoring programs, and (v) establish and implement an integrative and responsive muskox health surveillance system that is used to pro-actively inform wildlife management, public health, and land-use policy and decisions. We will work closely with communities of the Inuvialuit and Kitikmeot regions to do this research and develop and implement the surveillance program. There will be extensive training of northerners, as well as youth, graduate and undergraduate students through formal and informal classroom and on-the-land experiences. Our partners include local, regional, and territorial wildlife hunter and trapper organizations, industry, government, academia and local resource users. Ultimately we will use a combination of scientific, traditional and local knowledge and engagement to evaluate and monitor the health and vulnerability of muskoxen in a rapidly changing Arctic. Tools, techniques, and programs developed, together with extensive training of both northerners and southerners, will lead to improved technical and human resources for wildlife health monitoring and enhancement of food security across the North.

KEY MESSAGES

- Muskox health and resilience is important for ecosystem function, food security, and cultural integrity in northern Canada.
- Climate change and other ecological changes are affecting the health of wildlife in northern ecosystems.
- Recent significant disease-related declines of muskoxen in the western Arctic Archipelago are of concern to communities, biologists, and public health professionals.
- Our work in 2015-16 suggests that health of muskoxen in the western Arctic Archipelago is declining and that they may have low resilience to ongoing environmental changes and pathogen challenges.
    - » Local and traditional knowledge collected in 2014-15 indicate muskox populations have been declining since the mid-2000s, with smaller group sizes, fewer younger animals, and more muskoxen found dead or in poorer condition.
    - » Muskox lungworms, first detected in 2008, continue to expand their range and increase their abundance on Victoria Island.
    - » We identified Orf (parapox) virus for the first time in muskoxen on Victoria Island.
    - » The bacterium *Erysipelothrix rhusiopathiae* continues to be associated with unusual deaths in muskoxen and preliminary results suggest it is also present in rodents, snow geese and a seal. Serological study also demonstrates caribou exposure to the bacterium.
    - » There is extremely low genetic variability among muskoxen on Victoria Island which may lead to increased vulnerability to diseases and climate change.

  - We have validated the method for extracting and quantifying stress hormones from qiviut and preliminary results suggest some populations are more stressed and that stress varies seasonally
- Muskox health surveillance is an essential activity to inform evidence based management and contribute to the protection of public health, including food security and safety.
- We are using ecological models based on data and metabolic theory of ecology to help inform our understanding of disease ecology, emergence and impacts in muskoxen.
- The involvement of local people through sampling and contribution of traditional and local knowledge (TEK/LEK) is essential to understand population dynamics and health status of local wildlife species, as well as ensuring that a surveillance system is relevant and adapted to the local context. Web-based tools, such as Arctic BioMap, can help to document animal health observations.

OBJECTIVES

1. Assess muskox health and vulnerability using scientific investigation and local and traditional ecological knowledge.
2. Understand risk factors associated with, and consequences of, recently emerging diseases including lungworms, Erysipelothrix, and orf virus.
3. Develop and implement an integrative and responsive monitoring and surveillance program.

INTRODUCTION

The muskox (*Ovibos moschatus*) is a keystone species for the Northern ecosystem and an important source of food for Arctic people, with a central role in community well-being, cultural heritage and identity (Gunn et al, 1991; Lent, 1999). Recent events have raised concern about the health status of free-ranging muskoxen in the Canadian Arctic, particularly in the Arctic Archipelago (Banks and Victoria Islands in the Northwest Territories and Nunavut) where population declines, multiple mortalities, and emergence of new diseases are occurring (Kutz et al, 2015; Leclerc, 2015; Davison et al, 2013; Tomaselli et al, submitted). In particular, muskox die-offs associated with the zoonotic bacteria *Erysipelothrix rhusiopathiae*, not previously reported in muskoxen, nor in the Arctic, the emergence and rapid range expansion of two protostrongylid lungworms, and the confirmation of contagious ecthyma or orf in muskoxen, combined together with significant muskox population declines, suggest changes in ecological conditions and cumulative stressors that can further lead to emerging diseases, mortality, and population level impacts. Moreover, rapid climate warming, which is a major concern in the Arctic, is leading to altered host-parasite interactions and disease emergence (Kutz et al, 2005; Kutz et al, 2009; Dobson, Molnar and Kutz, 2015), and has already had an important impact on both marine and terrestrial ecosystems (Post et al, 2013); muskoxen are equally vulnerable to these changes.

Our work aims to understand the health of muskoxen and factors that influence their health and develop a health surveillance framework for ongoing health monitoring and disease detection. We do this through a multi-faceted approach that integrates both scientific and local and traditional knowledge and engages multiple stakeholders. We seek to understand the ecology, impact, and future of endemic and emerging diseases through a combination of participatory epidemiology, ongoing sampling, disease investigation, and development of ecological models. Our research on muskox genetics addresses questions as to whether this species has the genetic capacity to adapt to its changing environment. Simultaneously, we also aim to develop a health surveillance framework. Wildlife health and disease surveillance is a key instrument to inform wildlife management and to contribute to the protection of public health, including food security and safety (Peterson and Ferro, 2012;

OIE, 2010). An effective muskox health surveillance system, accepted and implemented locally, is essential to meet these goals. A primary goal of our program has been the full engagement and participation of local people in designing and implementing a muskox health surveillance system. This approach ensures that detailed ethnoecological and ethnoveterinary knowledge important for such systems is recorded, and also ensures that the surveillance system is relevant and applicable in the local context (Mariner and Paskin, 2000; Catley et al, 2012). Scientific, local and traditional knowledge, together with predictive ecological models, will provide new insights into the threats to muskox health, the resilience of this species, and the socio-ecological context in which to interpret these findings.

ACTIVITIES

Timeframe and study area: This ArcticNet project began in spring 2015 and encompasses the Kitikmeot region, Nunavut, and Inuvik region, NWT. Additional sampling has been done in other arctic regions when further context has been required.

Objective 1. Assess muskox health and vulnerability using scientific investigation and local and traditional ecological knowledge:

Muskox Sampling: We established a successful muskox sampling program in partnership with outfitters and the Hunters and Trappers Organizations in Ikaluktutiak and Kugluktuk. Consultations and training occurred with the communities of Gjoa Haven and Bathurst Inlet and on their request they were supplied with sampling kits. Eighty sampling kits have been distributed among these communities. Samples from these collections will be analyzed in summer 2017. The community of Ulukhaktok engaged in collection of fecal samples for muskox lungworm range expansion studies, and provided hides for stress studies. Comprehensive sampling at planned community hunts are anticipated for 2016-2017.

Genetics: This research addresses questions as to whether muskoxen can rapidly adapt when faced with changing environments. Although muskoxen have survived through many extreme population lows, this has caused multiple bottlenecks leaving them genetically impoverished with low genetic variability. As a result, muskox populations are poorly equipped to deal with rapid changes in climate conditions, new pathogens and increasing environmental stress. One way to study their vulnerability is by looking at immunologically associated genetic diversity and distribution in relation to disease survival. This project will provide initial data on neutral genetic marker assessments and provide a means for future evaluations of the correlation between immunogenetic variation, disease presence and muskox fitness. Our objectives are:

1. To identify neutral genetic variation and structure in muskox populations,
2. To create an annotated genome for reference and creation of candidate genes,

Fecal and tissue muskox samples were obtained from Victoria Island, Banks Island, Sahtu Region, Kugluktuk, Kuujjuaq and Greenland. Samples from Victoria Island have been processed to date. Samples received were used to examine neutral genetics (181 samples) and establish the genome (one male muskox). 12 primer sets for neutral DNA were optimized and multiplex reactions were created and optimized for further investigations. 181 muskox samples were genotyped and structure analyses were completed.

Stress: Lab validation activities for quantification of cortisol and corticosterone from muskox qiviut were completed. Hide samples from 135 muskoxen harvested from 5 different communities were tested for these hormones. Preliminary trials to establish washing methods and evaluate reliability of liquid chromatography tandem mass spectrometry for quantification of corticosteroids in guard hair were completed. Additional samples from animals found dead in spring 2014, and those harvested in fall 2014 near Cambridge Bay and Ulukhaktok have been collected but not yet analyzed.

Traditional and Local Ecological Knowledge on Muskox Health: We documented local and traditional ecological knowledge in Ikaluktutiak to understand: the traditional food system; traditional and local knowledge about muskox population dynamics, health and disease status over time; environmental changes that might be associated with muskox population decline; and logistic and practicality of hunter based sample collection from harvested muskoxen. We did individual semi-structured interviews (Figure 1) and group interviews (Figure 2) followed by multiple feedback sessions to validate the analyzed data with participants.

Key informants were selected through the Kitikmeot Inuit Association and the local Hunters and Trappers Organization (purposeful sampling), as well as by asking participants to identify other key informants to include in the study (snow ball technique) (Green and Thorogood, 2014). Semi-structured interviews and participatory methods were used both in the individual and group interview setting. Interviews were audio-recorded and key information was systematically transcribed to provide the basis for further analysis. The transcripts were analyzed through thematic content analysis, using both deductive and inductive approaches to code themes.

Objective 2. Understand risk factors associated with, and consequences of, recently emerging diseases including lungworms, Erysipelothrix, and orf virus:

Ecological Models for Transmission Dynamics and Impacts of Parasites in Muskoxen: Understanding the mechanisms that are responsible for pathogen emergence, transmission and range expansions that are observed in the Canadian Arctic is important. We are combining the Metabolic Theory of Ecology (Molnár et al, 2013) with classical host-macroparasite population dynamics models (Anderson & May, 1978) to develop a general modelling framework for the impacts of climate change on these systems (Molnár PK, Paull S., manuscript in preparation). Parasite physiology, parasite life cycle, and transmission mode determine whether climate change results in an increase or decrease of parasitism. PhD student Alexander Nascou was recruited in September 2015 and is currently working on developing a species-specific model for the interacting host-parasite population dynamics of muskoxen and their lungworm *U. pallikuukensis.* Analyses currently focus on determining under what conditions this parasite can regulate host population sizes, for example, by depressing host populations to low levels, or through inducing host-parasite cycles.

Lungworm Ecology and Emergence: The goal of this component is to investigate the ecology and range expansion of two emerging muskox lungworms *Umingmakstrongylus pallikuukensis* and

Figure 1. Sequence of images representing some moments captured during the individual interviews.

Figure 2. Sequence of images representing some moments captured during the small group interviews.

Varestrongylus eleguneniensis in the Canadian Arctic and then to construct species distribution models for both lungworms and for the gastropod intermediate host and apply these to determine future lungworm distributions under climate changing scenarios.

Lungworm surveillance: Purposive and opportunistic fecal surveys of muskoxen and caribou were done focusing on Victoria Island but encompassing all of the Kitikmeot and some of the High Arctic in collaboration with local hunters, regional biologists, outfitters. Samples were analyzed using the beaker Baermann method (Forrester and Lankester, 1997) and larvae identified to species based on our previous work (Kafle et al, 2015).

Lungworm ecology: Determining temperature dependent development rates: *Deroceras laeve* (the main slug intermediate host for the lungworms) were infected with *V. eleguneniensis* L1 as per (Hoberg et al, 1995) and (Kutz et al, 2000) with some minor modifications. 200 larvae were provided per slug on a moistened filter paper for 6 hours with lettuce for food. After exposure, slugs were transferred to clean Petri dishes with moistened filter paper and fresh food (carrots and lettuce). Slugs were killed, digested in a pepsin hydrochloric acid solution, and examined daily to assess development rates.

Degree day modeling to estimate lungworm distribution: The temperature threshold and thermal constant for *U. pallikuukensis* used in Kutz et al (2001) were used along with satellite derived temperature data from global climate models to create degree day maps from the 1970s to present. Projections on potential range of the muskox lungworm were simulated under different climate changing scenarios. This work is in the preliminary phase and after we get the temperature dependency data for *V. eleguneniensis*, similar maps for this parasite will also be created and compared to those for *U. pallikuukensis*.

Erysipelothrix Ecology: *Erysipelothrix rhusiopathiae* has been identified as the cause of wide spread mortality and associated with muskox population declines in the western Arctic Archipelago. Our objectives are to (i) understand the geographic distribution, and (ii) determine the diversity of *E. rhusiopathiae* and if it is shared among species.

To address our first objective of determining exposure of muskoxen to *E. rhusiopathiae*, we used an ELISA test developed and validated in our lab specifically for muskoxen to test 237 archived serum samples.

To address our second objective of evaluating the diversity of *E. rhusiopathiae* strains in the Arctic and evidence for sharing among species, we used both purposeful and opportunistic sampling.

Small Mammal Survey: Field collections for small mammals and pathogens were done at multiple sites on Victoria Island, at Elu Inlet on the Kent Peninsula, and at Kugluktuk, Nunavut between 27 June and 17 August 2015. Previously collected specimens (multiple sites in NU and NWT) held at government wildlife facilities in Kugluktuk, NU and in Yellowknife, NWT were also examined. Liver, lung, spleen, heart, kidney, colon, and lymphatic tissues were collected and stored in liquid nitrogen until they could be cultured as per Wood (1965) and Bender et al (2009). In total 186 specimens were collected.

Waterfowl Survey: Field collection of cloacal swabs was done by Environment Canada during a snow goose banding project on Banks Island (Northwest Territories) between July 8th and July 20th 2015. Swabs were kept cool for up to 2 weeks prior to shipping to University of Calgary for testing. We obtained swabs from 577 individual snow geese.

Opportunistically collected wildlife: Ten muskoxen found dead in spring 2015 and one seal found dead in August 2015 on Victoria Island were sampled. Additional wildlife samples opportunistically collected and tested include: 76 muskox faecal samples (North Baffin Island); 51 tissues (liver, spleen, kidney, heart, lung, lymph nodes, tonsils, bone marrow, and colon) from 10 muskoxen (Victoria Island); 6 tissues (liver, spleen, kidney, heart, lung, and mesenteric lymph node) from a ringed seal (Victoria Island).

Orf Virus Detecetion and Ecology: Interviews and personal observations gathered in the last few years have suggested an increasing occurrence of muskoxen with lesions on their noses/muzzles consistent with Orf, a parapox virus. Lesions from eight muskoxen from Victoria Island - one in 2014 and seven in 2015 - were tested for orf virus. The lesions were present on the nose, lips, palate, legs, or nipples of muskoxen. Using polymerase chain reaction (PCR), purified DNA was tested for two different parapoxvirus genes in separate assays. One encoding for the putative viral envelope antigen (B2L), and the viral DNA polymerase (DPOL). Primers targeting the B2L and DPOL genes were described previously by Inoshima et al (2000) and Bracht et al (2006), respectively.

Other viruses, such as herpes virus, can also cause sores and lesions to develop on the skin and mucosal surfaces in humans and animals. All 2015 samples were screened for the herpes virus DNA-dependent DNA polymerase (HVDPOL) gene using PCR as described above and with published primers by Vandevanter et al (1996).

Arctic BioMap: Working with the Arctic Institute of North America and the Department of Geomatics Engineering, University of Calgary, we are developing Arctic BioMap. This is a network-enabled platform for arctic research and information sharing that enables members of the scientific community and northern residents to contribute observations on arctic animals for the purpose of biodiversity and health monitoring, assessment, research, management and education. We have built a lite tracking application to record community observations on animal sightings and health and have also built a prototype of the proposed real-time monitoring application and shared this with select communities in Yukon, Nunavut, and NWT this year.

RESULTS

Objective 1: Assess muskox health and vulnerability using scientific investigation and local and traditional ecological knowledge:

Muskox Sampling: Community-based sampling of harvested muskoxen is gaining momentum with the addition of 2 communities to the program in 2015. Samples will be analyzed in 2016.

Genetics:

Neutral Genetics: The 2015 year has produced new results for neutral genetics of muskox populations on Victoria Island and began genome analyses. We found very little genetic variation within samples (Table 1). Three of the optimized primers showed signs of null alleles due to a lack in variation and were removed from further analyses leaving 9 loci to analyze the neutral genetic structure. The results for this structure found no individuals that could be assigned to any cluster as its probability values remained close to

0.500 with the highest association percentage at 0.505. As they were all below all three levels of stringency, all remained unassigned. The bar graph gives a visual representation of the percentage data as a result of the structure analyses (Figure 3) (Table 1).

Genome: DNA from a male muskox was extracted and library preparation of 4 Paired end and 2 mate pair libraries were completed for genome analyses. Data will be used from this to create a genome for the muskox.

Stress: A total of 135 hides were sampled from Sachs Harbour, Ulukhaktok, Paulatuk, Kugluktuk and Cambridge Bay. A significant seasonal pattern, with qiviut cortisol increasing from August through to the following spring was detected. (Figure 4). There were some differences between populations with samples submitted from Cambridge Bay having the highest cortisol levels. A manuscript of these results ('First insights into the use of cortisol in hair as an indicator of population health in muskoxen of the Canadian Arctic') will be submitted in spring 2016.

Traditional and Local Ecological Knowledge on Muskox Health: We did semi-structured interviews with 30 individuals and 7 group interviews (19 participants total) and 31 participants attended the feedback sessions. To date the results on traditional and local knowledge about muskox population dynamics, health and disease status over time have been analyzed and validated with the community.

According to participants, muskoxen were rare in the 1960s until the 1970s but became abundant from the 1980s to early 2000s. According to participants' cumulative perception, muskox populations in the Ikaluktutiak area had started to decline around mid-2000s, with a major decline after 2010. This decline was accompanied by a decrease in the proportion of juveniles, a decrease in body condition *"[today] you would be very lucky to get an animal with 3 cm of back fat, but usually they have 1 cm or nothing",* and an increase of diseased and dead animals. Although the majority of the diseases had been observed prior to the decline, some of them (e.g. swollen joint and limping animals) were observed more commonly since the decline, and others (e.g. scabby orf-like lesions) were considered new to the area. Additionally, acute deaths of muskoxen and disease outbreaks or die-off events, were only observed during the declining period. A seasonal and temporal pattern in those "acute mortality" cases was observed, with more events observed in the summer and with a peak of cases in 2012.

Figure 3. Bar Plot of structure data. Two inferred clusters represented by red and green coloring. No sample could be attributed to either cluster as attribution n probability rests around 50% for all samples as seen by the split of red and green evenly across the plot.

Table 1. Summary of genetic variation within 9 neutral microsatellite loci tested. Consists of the number of samples tested, the number of alleles found at each locus, the observed heterozygosity (Ho) and the expected heterozygosity (He)

Locus	Number of alleles	Sample number	Ho	He
OM58-06	2	92	0.054	0.053
OM51-19	4	90	0.256	0.233
OM54-23	3	91	0.132	0.125
OM53-38	3	83	0.422	0.484
OM53-12	2	89	0.438	0.477
OM55-04	5	87	0.103	0.101
OM50-8	2	89	0.034	0.055
MoDIAS 3	2	86	0.035	0.034
MoDIAS 2	2	93	0.484	0.339

Objective 2: Understand risk factors associated with, and consequences of, recently emerging diseases including lungworms, Erysipelothrix, and orf virus:

Lungworm Ecology and Emergence: Fecal surveys: Results from fecal samples analyzed in 2015/2016 further support that there has been substantial range expansion of U. pallikuukensis and V. eleguneniensis to the higher latitudes. Umingmakstrongylus pallikuukensis has expanded its range more rapidly and covers a broader geographical range than V. eleguneniensis (Figure 5). We detected U. pallikuukensis in 51% of muskox fecal samples (n=64) collected around Ulukhaktok. The intensity of infection was low compared to other areas of the island (Median larva per gram of feces- 1.76). Similarly, 20% (n=25) of the caribou fecal samples had lungworms. The species confirmation is underway but these animals are suspected to be co-infected by V. eleguneniensis and another protostrongylid, Parelaphostrongylus andersoni. The latter, if confirmed, will be the first report of this parasite in Dolphin and Union caribou herd. Fecal samples tested from high arctic islands were negative for protostrongylid lungworms.

Parasite ecology: Temperature dependent development trials at 3 temperatures suggest that *V. eleguneniensis* has a higher development threshold and requires more degree days of heating than *U. pallikuukensis* to develop to the infective stage.

Modeling distribution: Preliminary degree day modelling for *U. pallikuukensis* suggests that historically, temperatures on Victoria Island were unsuitable to support an annual life cycle but that recent warming has made most of the regions of Victoria Island suitable.

Erysipelothrix Ecology: *Serology*: Results from Banks Island (NWT) indicate that *Erysipelothrix* was circulating in muskoxen in 2001; high seroprevalence and antibody titers were observed in the fall of 2012 following the summer mortality event associated with *Erysipelothrix* infection. There was also serological evidence of exposure to *Erysipelothrix* in muskoxen from Victoria Island and Kugluktuk (NU) and Alaska.

Bacterial Culture: 76 muskox fecal samples were all negative for *Erysipelothrix* by culture and direct PCR. 39 of the 51 muskox tissues grew bacteria on selective culture and will be further analyzed by PCR in spring 2016. 37 of 186 rodent samples grew bacteria on

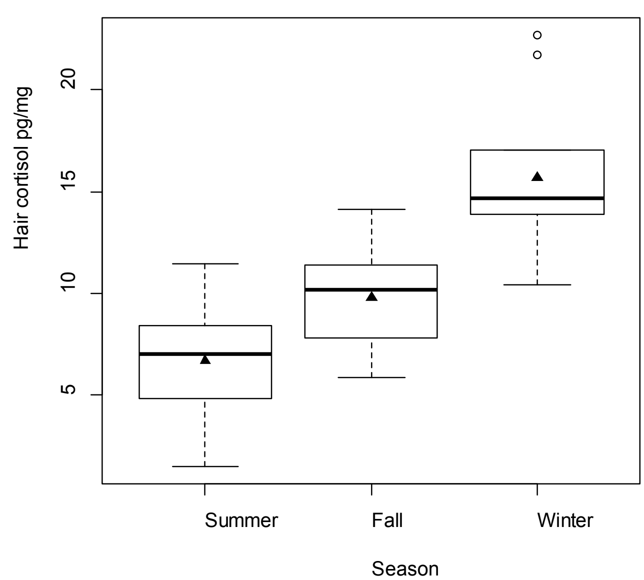

Figure 4. Seasonal patterns of qiviut cortisol (pg/mg) in adult male muskoxen hunted in Cambridge Bay in 2014 (n=51).

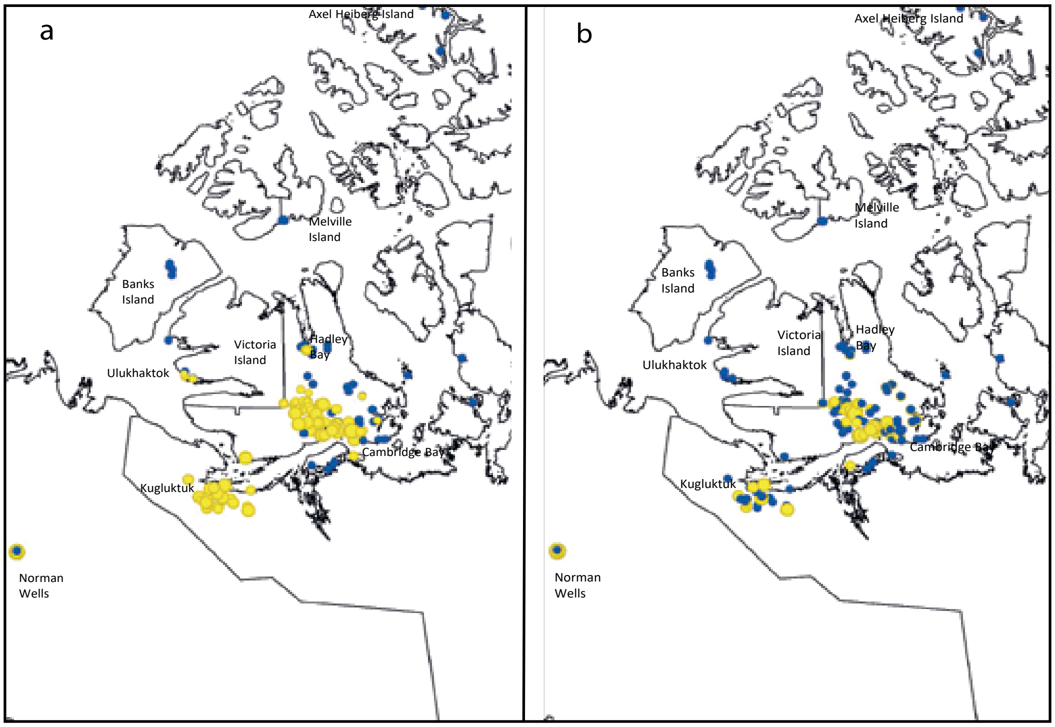

Figure 5. Distribution of the two lungworms based on fecal samples collected in 2013-2015. The size of yellow circles indicates the severity of infection. The blue circles indicate the sites tested negative for lungworms. a) Distribution of Umingmakstrongylus pallikuukensis. b) Distribution of Varestrongylus eleguneniensis.

selective culture and will be further analyzed by PCR in spring 2016.

Snow geese samples were pooled in batches of up to 4 animals. In total 90 of 149 samples grew bacteria on selective culture and will be further analyzed in spring 2016.

Isolates confirmed by PCR as *E. rhusiopathiae* will be further characterized through whole Genome sequencing in 2016/17.

Orf Virus Identification Ecology: The muskox sampled in 2014 was positive for the B2L and DPOL gene of Parapoxviridae (data not shown). This is described in our paper submitted to the Journal of Wildlife Diseases in December of 2015. The seven animals sampled in 2015 were positive for orf virus and further characterization is underway.Preliminary analyses suggest that 5 of 7 muskoxen tested were also positive for a herpes virus. This will be further characterized.

Arctic BioMap: Kluane First Nation and Carcross Tagish First Nation in Yukon and the communities of Kugluktuk and Cambridge Bay in Nunavut expressed further interest in collaborating on this project and in fall 2015 we did focus group workshops in the Kluane Lake, Carcross, and Kugluktuk to understand community needs for building the BioMap real-time monitoring program. The workshop explored local environmental and wildlife health, and social issues of concern due to climate change and will build key metrics of local interest to build the BioMap monitoring program. Workshop participants included community elders, hunters, and youth, and government wildlife professionals. The three focus groups included close to 30 participants. A paper describing this work was submitted to *PLOS 1* in January 2016 (Panikkar, et al, submitted).

DISCUSSION

Our ArcticNet funded research has lead to substantial new knowledge generation in 2015. From genetics, to traditional knowledge, our understanding of muskox health, ecology, and resilience has greatly expanded.

Our community-based muskox sampling program was refined and expanded to new communities, in response to their requests. Samples from each animal are distributed among each of our projects providing a comprehensive assessment of the health of each individual (genetic, stress, infectious disease) and hunter comments are incorporated into these analyses.

Our work on muskox genetics has demonstrated so far an extremely low amount of variation. The first indication of variation can be seen in the number of alleles that are present at each locus. We found very low amounts of allelic diversity within the loci used with a high of 5 alleles at OM55-05 and an average of 2.78 alleles. Another measure of genetic diversity is the expected and observed heterozygosity of the muskox populations. Observed heterozygosity is the actual amount of heterozygosity seen in a population while expected heterozygosity is the level of heterozygosity expected if the population was within Hardy-Weinberg equilibrium. When comparing the two, they should be relatively close, otherwise it is outside of Hardy-Weinberg equilibrium. In this study, the observed and expected heterozygosity of each locus was fairly similar. However, the levels of observed and expected heterozygosity are very low. The highest observed heterozygosity is 0.484 with majority of the loci at around 0.2. In comparison to other ungulate species (observed heterozygosity is 0.7), this is extremely low.

Low levels of genetic variation have huge implications for the survival of muskoxen. While species have the ability to adapt to changing selective pressures, like diseases, their genetic variation is ultimately the real measure of their capacity to adapt. If they have nothing to work with in the first place due to low genetic variation, there is a possibility that none of the alleles still present in the population are suitable for survival. In this case, selective pressures like diseases will likely kill most of the muskox populations.

We used structure software to determine the amount of neutral population structure between muskox populations which could allow inferences about the level of gene flow to be made. Our results suggest no genetic structure between the sampled animals on Victoria Island indicating high levels of gene flow between populations. This is not particularly surprising given that the island was probably colonized by an extreme bottlenecked population that resulted when muskoxen were almost extirpated from Victoria Island by the early 1900s.

Stress can lead to increased vulnerability to infectious disease and other threats. Our goal is to evaluate the use of hair stress hormones as a method that can be incorporated into health surveillance protocols as an indicator of health. Our methods demonstrate reliable quantification of cortisol and corticosterone from qiviut, and preliminary findings suggest good success with guard hairs as well. Our results provide the first data on hair corticosteroids in muskoxen. These results suggest some differences among populations with different trajectories, and demonstrate an unexpected significant seasonal increase from summer through to the next spring. This highlights the importance of controlling for season when analyzing stress. Next we will use existing hunter-based samples and data together with new comprehensive scientific sampling to evaluate the relationship between hair corticosteroids and other indicators of fitness in individual animals and populations.

The data compiled from traditional and local knowledge holders suggested a decline in muskox populations in the Cambridge Bay area since the mid-2000s, with observations of overall deterioration of health status of the animals, measured as poorer body condition, increased observation of diseases (reported as abnormalities and syndromes), and die-off events. The observations of a decline in the juvenile age class suggest perhaps poorer reproduction of muskoxen, which might be a consequence by poor nutritional status, or may be linked to infectious disease affecting conception, maternal health, or direct impacts of disease on the young. Participants' description of muskox "acute mortality events" allowed to better characterize and quantify muskox die-offs that had been under-reported in the area, and increases our knowledge about seasonal patterns of muskox disease outbreaks. Engagement of community members in interviews was exceptional as was the quantity and quality of the data collected. Results were presented at the muskox management workshop and incorporated into management plans.

The geographic range of *U. pallikuukensis* and *V. eleguneniensis* was previously thought to be limited to the mainland of the Canadian Arctic, but these parasites were detected from southern Victoria Island in 2008 and 2010, respectively (Kutz et al, 2013). The abundance of both lungworms increased around southern Victoria in the subsequent years (Kutz et al, 2013; Kafle unpubl. data) and our results show that there has been substantial range expansion of *U. pallikuukensis* as far north as Hadley Bay (300km north of Cambridge Bay) and Ulukhaktok, and a latitudinal gradient of decreasing intensity of infection with latitude. Our results also showed the range expansion of *V. eleguneniensis,* which was limited to approximately 150 km north of Cambridge Bay. *Varestrongylus eleguneniensis* is a multi host parasite, carried and maintained by caribou in addition to muskoxen (Verocai et al, 2014), and thus was expected to cover a broader geographical range and expand more rapidly than *U. pallikuukensis.* The presence of lungworms in caribou from the Dolphin and Union (DU) herd further supports the repeated introduction of lungworms to Victoria Island as this herd migrates annually between the mainland and island. The slower range expansion of *V. eleguneniensis* compared to *U. pallikuukensis* may be associated with differences in thermal dependencies (threshold for development, thermal constant). Our preliminary results from the temperature dependent development experiment of *V. eleguneniensis* and the observed differences in the ranges of *V. eleguniensis* and *U. pallikuukensis* further supports this. However, differences in fecundity and other aspects of the ecology of these parasites need to be considered.

Previous study by Kutz et al (2013) using degree-day modelling approach, suggested that the range expansion of *U. pallikuukensis* to Arctic Archipelago was in part associated with the warming climate. This approach did not, however, include intermediate host dynamics, which are also affected by climate change. In 2016 we will use the distribution of parasite and intermediate host, temperature sensitive life history traits of the parasite, and state of the art global climate models to create habitat suitability maps from the past to future under different climate changing scenarios. This will allow us to evaluate the role of climate as a potential driver of range expansion and project the range of the lungworms in the future, which has management implications. Additional ecological modeling of increasing complexity will be done for these lungworms and other pathogens incorporating the metabolic theory of ecology and host population dynamics to better understand the impacts of these pathogens on muskox populations.

Our results demonstrate seropositivity in all muskox herds tested, suggesting that exposure to *Erysipelothrix* is widespread in muskox populations. The bacterium is opportunistic, and the apparent recent increased occurrence of disease associated with this bacterium may be a result of changing ecological conditions causing increased exposure or susceptibility. Preliminary culture findings suggest that *E. rhusiopathiae* was present in muskoxen found dead in spring 2015, a dead seal, and apparently healthy waterfowl and rodents. Whole genome sequencing and several bioinformatics tools will be employed to determine the population structure and examine lineage-specific traits. For instance, specific lineages may be strongly associated with particular host species, geographic origin, or phenotypic characteristics such as virulence.

We have demonstrated that the parapox virus 'orf' is present and causing significant morbidity of muskoxen on Victoria Island. It is unusual for orf viruses to be found in adult animals, and the presence in muskoxen suggests that these animals may be immunologically compromised. Additionally, our preliminary findings of a herpes virus in these lesions may further support a hypothesis of immunocompromise as this group of viruses are also often activated by stress. We will continue sampling for and characterizing these viruses.

Together, the projects above have provided considerable scientific data and local and traditional knowledge that will serve as a foundation for a muskox health surveillance framework. Multiple tools, including web-based programs such as Arctic BioMap, community based and scientific sampling, ongoing and systematic collection of local observations, and modeling approaches will come together to both direct the content and processes for a surveillance program while at the same time informing on muskox conservation and public health and food safety and security issues.

CONCLUSION

This body of works constitutes a multi-agency and multidisciplinary approach to understanding the health and resilience of muskoxen in a changing Arctic. By taking a holistic approach to evaluating health and integrating multiple disciplines and sources of knowledge (scientific, local, and traditional) we have made substantial advances in our understanding of the current status of muskox health, from condition, infectious disease, and genetics. We are delving into the ecology, transmission, and impacts of pathogens using a combination of field, laboratory, and modeling studies. We are also testing potential indicators of health (e.g., stress), and developing a health surveillance framework that uses multifaceted approaches with LEK, TEK, Arctic BioMap, and community, government, and scientific sampling.

This research is necessary to understand what effect changing environments will have on wildlife health and sustainability, food safety and security, and health of northern communities. Additionally, through this research we will establish programs for ongoing health surveillance and begin to develop strategies to mitigate the negative impacts the changing arctic environment has on muskox populations.

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Water Security and Quality in a Changing Arctic

Project Leaders

Scott Lamoureux (Queen's University); Melissa Lafrenière (Queen's University)

Network Investigators

Pierre Francus (Institut national de la recherche scientifique - Eau, Terre et Environnement)
Jan Franssen (Université de Montréal)
Elyn Humphreys (Carleton University)
Derek Muir (University of Guelph)
Murray Richardson (Carleton University)
Allison Rutter (Queen's University)
Neal Scott (Queen's University)
Myrna Simpson (University of Toronto)
Vincent St. Louis (University of Alberta)
Paul Treitz (Queen's University)

Collaborators

Jane Kirk (University of Alberta)
Jamal Shirley (Nunavut Research Institute)
Joseph White (Baylor University)

HQP

Nanfeng Liu, Doctoral Student (Queen's University)
Michel Paquette, Doctoral Student (Université de Montréal)
Ashley Rudy, Doctoral Student (Queen's University)
Landscape controls over permafrost disturbance
Gabriel Chiasson-Poirier, Honours Undergraduate Student (Université de Montréal)
Peter Crawford, Honours Undergraduate Student (Queen's University)
Siohahn McCarter, Honours Undergraduate Student (Queen's University)
Bridgit Rusk, Honours Undergraduate Student (Queen's University)
Gillian Thiel, Honours Undergraduate Student (Queen's University)
Sean Arruda, Masters Student (Trent University)
Amy Blaser, Masters Student (Queen's University)
Christopher Bolduc, Masters Student (Queen's University)
Emma Buckley, Masters Student (Queen's University)
Relationships between vegetation NDVI and carbon exchange at high frequency in high Arctic plant communities
Rebecca Edwards, Masters Student (Queen's University)
Matthew Gillman, Masters Student (Queen's University)
Elizabeta Kjikjerkovska, Masters Student (Queen's University)
Kaitlyn Roberts, Masters Student (Queen's University)
Keegan Smith, Masters Student (Carleton University)
Benjamin Amann, Post-Doctoral Fellow (Queen's University)
Ana Cabrerizo, Post-Doctoral Fellow (Environment Canada - Canada Centre for Inland Waters)
Julien Fouché, Post-Doctoral Fellow (Centre d'études nordiques)
Alexandre Normandeau, Post-Doctoral Fellow (Queen's University)
JunJian Wang, Post-Doctoral Fellow (University of Toronto)
Graham Cairns, Research Associate (Queen's University)

Maya Abou-Ghanem, Technical Staff (University of Alberta)
Yue (Ruby) Jiang, Technical Staff (University of Alberta)
Steve Koziar, Technical Staff (Queen's University)
Koster Sonja, Technical Staff (Queen's University)
Isolina Zazzara-Yu, Undergraduate Student (Queen's University)

Northern HQP

Jessica Peters, Northern Research Staff (Queen's University)

ABSTRACT

Water is a crucial component of ecosystems and plays a vital role, in conjunction with climate and permafrost, in the stability of arctic landscapes and ecosystems. The security of water for ecosystem services, community use and economic development depends on knowledge by northerners regarding the impact of climate and permafrost change on water and the interactions these changes have with other terrestrial components like vegetation and animals. Projected climate changes are anticipated to substantially affect winter snowpack and melt season conditions that will in turn affect hydrological response, water quality, as well as permafrost and landscape stability. These changes will affect related watershed processes such as nutrient and contaminant cycling and fluxes, erosion, primary production of tundra vegetation and greenhouse gas exchange with the atmosphere. However, there is considerable scientific uncertainty with regards to many of these components, and few comprehensive datasets to assess the potential impacts of climate changes on water resources in the Arctic. Moreover, there is a compelling need to support and develop capacity in northern communities to direct and participate in relevant research, and to link knowledge generated by different research communities.

This project seeks to address these gaps by pursing both state of the art, integrated watershed research, and to build capacity in communities to undertaken long term, sustainable watershed research in the Arctic. The project will carry out research at the Cape Bounty Arctic Watershed Observatory (CBAWO) on Melville Island near the Nunavut/ NWT border. With support from ArcticNet since 2005, research at CBAWO has focused on an integrated approach to identify the key processes that link watershed and landscape processes and to model their vulnerability and response to climate change. This location is the only comprehensive watershed monitoring observatory in the Canadian Arctic Archipelago and provides key insights into landscape and watershed processes in the western islands. With support and collaboration with numerous community stakeholders, we have expanded this watershed approach to the Apex River near Iqaluit. Since 2013, this project has undertaken to build local research capacity, engage stakeholders, and attract research interest to a watershed with significant community interest. This project seeks to substantially expand the Apex River research as a means of transferring knowledge gained at CBAWO, while also advancing our fundamental knowledge of water and terrestrial change in both locations. The multidisciplinary research team has diverse expertise that has allowed them to develop an integrated approach to resolving uncertainties in the response of Arctic watersheds to climate change.

KEY MESSAGES

- At Cape Bounty (CBAWO) we continue to advance the most comprehensive landscape and hydrological research program in the Canadian Arctic. Our research at the Apex River builds on our integrated research at CBAWO to benefit water security concerns in the Iqaluit region, and has fostered strong local research partnerships.
- Late season water availability and quality is linked to active layer thaw depth and soil water drainage pathways and constitutes a key sensitivity for surface water.
- Late season runoff and runoff from disturbances at CBAWO is nutrient rich, and channels fed by emerging subsurface water contain significant algal blooms.
- The age and composition of dissolved organic matter in runoff is altered by climate change impacts in the High Arctic.
- Our research is tracking the rapid chemical transition of CBAWO lakes and we are building evidence to demonstrate this may represent a potentially widespread risk to Arctic lakes.

- Spatial patterns of soil moisture within wet sedge meadows at CBAWO alter permafrost thaw and net carbon exchange with the atmosphere, with impacts on runoff in the catchment.
- Results from our work within the Apex River watershed revealed the potential for significant advancements in our understanding of subsurface hydrological processes in permafrost environments.
- Thermal and natural tracer investigations in the Apex River watershed indicate that subsurface waters (potentially ground ice) contribute to late season runoff along the Apex River. The contributions appear to be highly localized and ephemeral.
- Through collaborations with Nunavut Research Institute and NAC-ETP students we have made significant progress in quantifying end of winter snow distribution in the topographically complex Apex River watershed.
- We were able to provide support for ArcticNet researchers at our 'Iqaluit Analytical Services Unit' located at the Iqaluit NRI facility and Inuit students in an Environmental Sampling and Analysis Training Program.

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 climate 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. First, we propose to use 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 new (2013+) collaborative research program in the Apex River watershed near Iqaluit, NU. Research at the Apex River is motivated by interest and concerns about changes to river flow and water quality by local decision makers, particularly the City of Iqaluit and residents.

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.

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 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

Our field and research programs are located at the Cape Bounty Arctic Watershed Observatory (CBAWO) in the High Arctic (Figure 1A), and the Apex River on southern Baffin Island near Iqaluit (Figure 1B). Each is presented separately for clarity.

Cape Bounty (CBAWO)

CBAWO is the longest comprehensive watershed program in the Canadian Arctic. Activities in 2015-16 focused on investigating changing water pathways and water sources, as well the effects of thermal perturbations and physical disturbance of the permafrost, and climate-induced vegetation changes on water quality. We further maintained systems to collect long term climate, river, soil and lake data that have become critical to understand the impacts of rapid environmental change (Figure 2).

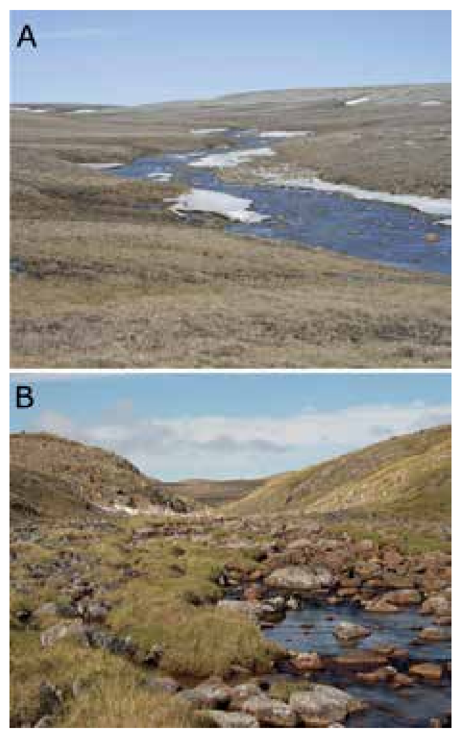

Figure 1. A) Cape Bounty Arctic Watershed Observatory (CBAWO) during late snowmelt; B) Apex River during summer (photos by S. Lamoureux).

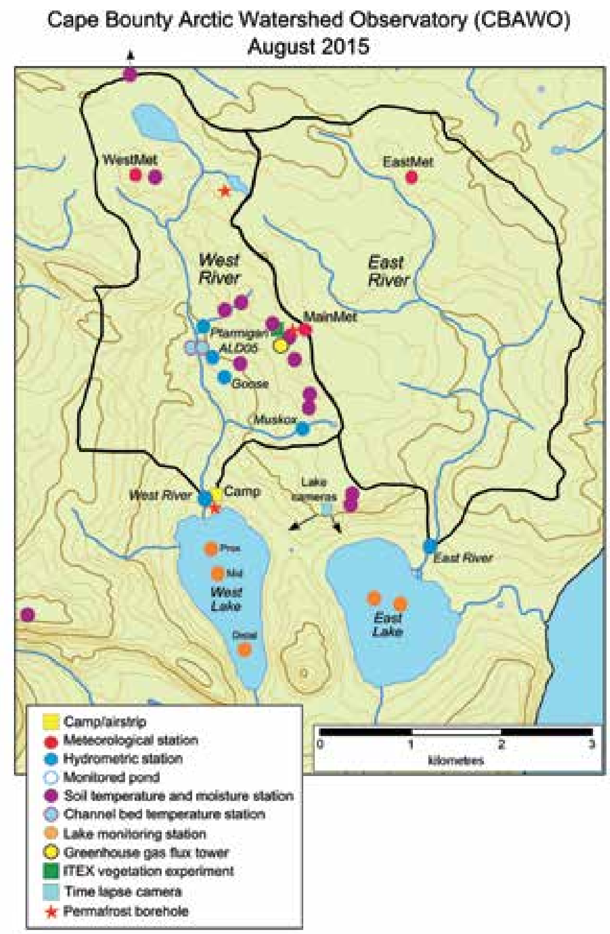

Figure 2. Field stations at CBAWO.

Hydrological research focused on several key elements. We installed a large number of new soil temperature and soil water sampling stations to support intensive research in future years. Soil porewater pressure sensors were also installed in key locations to investigate processes that generate landscape instability. Ground penetrating radar (GPR) transects were completed in key catchment settings, and paired with permafrost cores to improve GPR interpretations, and to provide samples for hydrological research.

Water sampling was undertaken until August 26, the latest field sampling to date at CBAWO. River and lake water samples were processed for water chemistry, stable isotopes, nutrients and contaminants. Water column profiles were also completed at three lakes, extending records to 13 years. Additionally, a full sidescan sonar and acoustic survey was completed for two lakes, to support investigation of long term change.

Dissolved organic matter loading in rivers and streams can alter water quality as well as biogeochemical cycling. Recent and unprecedented warming in the High Arctic has accelerated permafrost thaw, which subsequently releases large amounts of carbon into nearby soils and water. Much of this carbon is rich in easily degraded substrates (labile carbon), which stimulates microbial respiration and the flux of atmospheric CO_2 (Pautler et al., 2010). Furthermore, our previous work has found that permafrost-derived carbon is also entering aquatic systems (Grewer et al., 2015). To test this, we collected samples from the West River for detailed geochemical analyses, which includes molecular-level tools for ascertaining the organic geochemistry and age of the DOM using isotope, fluorescence and elemental approaches. We also collected surface water samples for DOM characterisation from soil lysimeters, areas where subsurface water is emerging at breaks in slopes, or as mud and fluid ejections in disturbed areas, or in small undisturbed ponds to characterize the composition of nutrient, DOM, and stable isotopes.

To further investigate the impact of climate change (warming and snow accumulation) on the composition of DOM and nutrients in High Arctic soils, we installed data loggers and sensors to monitor soil moisture, temperature and electrical conductivity and lysimeters (to collect sample for DOM fluorescence, and C:N analyses) in the nine ITEX plots. This experiment will allow us to investigate the impact of more than seven years of experimentation with climatic variables including warming by open top chamber and snow augmentation, has on soil water carbon and nutrient budgets.

Dissolved greenhouse gas samples were collected from both lakes. Surface and depth profiles of these greenhouse gases in both East and West lakes to determine zones of production or consumption. Field work focused on collection and analysis of water from the lakes in 2015 for analysis of total mercury (THg) and methyl mercury (MeHg). Landlocked arctic char were collected from East and West lakes August 1-4, 2015. Fish were dissected within 1 to 4 h after collection and subsamples of muscle+skin, liver, otoliths, and GI tract were frozen on site (-20°C) for transport. Water and fish were shipped in Environment Canada (Burlington) in early August where THg and MeHg were determined using standard U.S. EPA analytical protocols.

Terrestrial research in 2015 focused on examining the impacts of changes in temperature and snowfall on vegetation dynamics, and factors regulating net carbon exchange in wet sedge meadows. The first activity was carried out in collaboration with Greg Henry (UBC), who helped establish an experiment at CBAWO in 2008 as part of the International Tundra Experiment (ITEX). This experiment is unique to the network in that it examines the individual, and interactive, effects of enhanced temperature and snowfall on permafrost and ecosystem dynamics. We used standard protocols from ITEX (Henry and Molau, 1997) to measure vegetation properties (Figure 3) and impacts of experimental treatments on species diversity (six years later) and plant phenology. We also determined

Figure 3. Static chamber measurements of net carbon exchange (photo by N. Scott).

Figure 4. Point frame measurements of plant response to enhanced snow deposition (photo by I. Zazzara-Yu).

the treatment effects on permafrost dynamics. Static chamber methods (Figure 4) were used to measure the impacts of the treatments on net carbon exchange.

We also completed our second year of high frequency net CO_2 flux measurements from wet sedge meadows. In 2015, we collected data to explore spatial patterns of net carbon flux from wet sedge meadows. These results will help us develop more robust models of net carbon exchange that can be used to predict ecosystem and watershed response to future changes in climate (both temperature and precipitation).

Apex River

In the spring of 2015 a snow surveying campaign was initiated for the Apex River watershed, in close partnership with Nunavut Research Institute (NRI) and Nunavut Arctic College Environmental Technology Program (NAC-ETP). Snow survey training was first conducted at the NAC-ETP annual spring field camp at Crazy Lake with 2nd year students. After field camp, similar work was conducted in the Apex River watershed. Six NAC-ETP students participated in this work and their land skills and knowledge of local terrain proved critical in the development of our sampling protocol, which will be repeated in each year of the study. These data were combined with the broader-scale snowmobile surveys and used to develop a preliminary terrain model of snow accumulation using a high-resolution (~ 1 m) digital elevation model. Additionally, a new meteorological station was installed that will be used in all years of the study and beyond, and we are working with NRI staff and scientists from Environment Canada to develop a sustained program of climatological monitoring within the Apex River watershed. Near the new meteorological tower, two large wooden snowmelt lysimeters were installed to collect high-temporal resolution snowmelt output. Finally, melt water output from six different locations were collected every 2-3 days throughout the peak melt period and analyzed for stable isotopes of water (Figure 5).

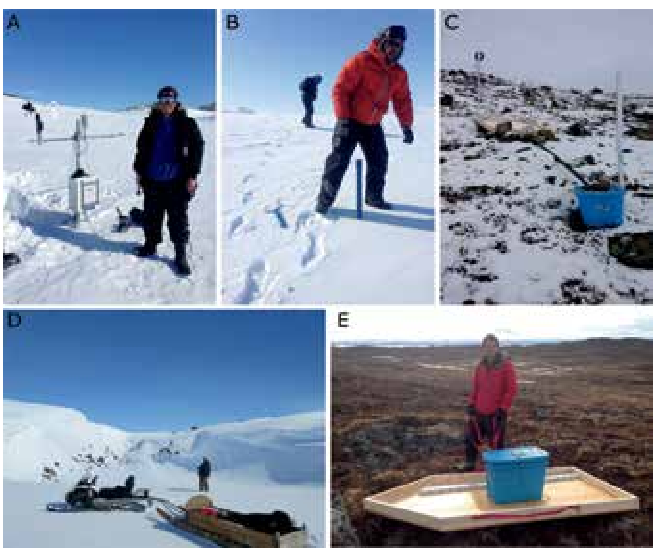

Figure 5. A) K. Smith in front of meteorological station in the Apex River watershed, spring 2015 (photo by M. Richardson); B) Randy Hinalik collecting snow water equivalent data at a sampling location in the Apex River watershed (photo by M. Richardson); C) One of two snowmelt lysimeters installed in the Apex River watershed two monitor snowmelt outputs in the spring of 2016 (photo by J. Shirley); D) Angulalik "Angut" Pedersen on a break near a deep snow-filled valley during spring 2015 snow surveys in the Apex River watershed (photo by K. Smith); E) Keegan Smith during a break on an overland carry of wooden snowmelt lysimeters in the Apex River watershed (photo by M. Richardson).

Extending successful efforts at CBAWO in 2014, we conducted field studies in July and early August to define the spatio-temporal patterns to subsurface inflows to the Apex River and examined how these patterns related to local landscape features. We undertook fine scale mapping (1-m resolution) of surface water temperature and conductivity along four river segments (Figures 6 and 7). Local variations in temperature and conductivity were used to infer the location of subsurface inputs to the river. Additionally, at each of our study sites we undertook detailed mapping of surface deposits and vegetation adjacent to the river. At a selection of sites representative of the various types of surface deposits, we installed mini-piezometer networks to characterize subsurface flows between hillslopes and the river.

In cooperation with NRI collaborator J. Shirley, NRI staff, and ETP summer students, we conducted an integrated hydrological and water quality monitoring program across the Apex River watershed to improve our understanding of the seasonal evolution of water sources and pathways and how these influence water quality parameters. Four stream gauging stations were installed to measure flow level (Figure 8), and regular discharge measurements were taken to derive rating curves and seasonal discharge records. We conducted a coordinated sampling program at these four sites from the onset of runoff in May until freeze up in October. Runoff was collected up to three times weekly at the four sites including samples for natural tracers (conservative dissolved ions, and stable isotopes of water) to investigate water sources and flow path; and samples for quality parameters (dissolved ions, nutrients, and DOM dissolved metals and microbial counts). In addition, we conducted high-resolution measurements just downstream of the confluence (CF). Previous stable isotope data suggest that this area is subject to inputs of significant subsurface water in late season. Detailed measurements of water temperature and electrical conductivity, and samples for stable isotopes and dissolved ions were taken at the site regularly during the season.

Figure 6. Temperature and conductivity profiling. An instrumented floating platform was trawled along channel margins to detect local anomalies in temperature and electrical conductivity (photo by G. Chiasson-Poirier).

The NRI provided advice to help plan the 2015 field research activities in the Apex Watershed study. NRI research intern J. Peters participated in routine water sampling and stream discharge gauging activities for the duration of the summer. NRI also provided space, supplies, field and lab equipment, and ground transportation, to support sample collection and processing by research teams. NRI provided general oversight of all field activities, coordinated lab safety training for student researchers, and liaised daily with field researchers to ensure safe and successful field research. Upon departure of Queen's research team members in late August, NRI maintained routine water quality and tracer sampling at a key monitoring site until freeze-up to ensure full season coverage.

NRI staff also conducted the regular sampling of Apex River water to detect and enumerate microbial indicator bacteria (total coliforms and *E. coli*). A total of 61 water samples were collected from the Apex "confluence" (CF) site (Figure 8) following Standard Methods for the Analysis of Water and Wastewater. Samples were tested in the NRI laboratories using the *Colilert* defined substrates technology. Microbial indicator data will be incorporated in analyses of climate and environmental controls on seasonal water quality changes in the Apex by Queen's undergraduate student G. Thiel as part of her undergraduate thesis project.

In our terrestrial research program, we collected percent vegetation cover (PVC) data (Figure 9) and fraction of absorbed photosynthetic active radiation (FAPAR) data (Figure 10) for contrasting vegetation types found within the Apex River watershed. These data are now being analysed and examined in relation to satellite spectral data/indices derived from high spatial resolution WorldView-3 data collected in July 2015. The WorldView-3 data are also being classified to derive a detailed vegetation map of the Apex River watershed. Finally, at both field sites (Apex River and CBAWO) we are examining Landsat time series data to determine changes in vegetation spectral indices during the period 1982-2015. This will enable us to determine if there has been an increase in productivity or change in vegetation at these two sites over the past 30 years.

Figure 7. Temperature and conductivity profiling – downstream of the confluence (photo by J. Franssen).

Through collaborations with Paul Budkewitsch of Aboriginal Affairs and Northern Development, we were able to connect with a resident (Natashia Allakariallak) working for the Nunavut Regional Office that was interested in our project. She spent a day with us in the field getting hands-on experience about collecting PVC data and learning more about the vegetation located in the watershed.

Iqaluit Analytical Services Unit (IASU) once again offered its Environmental Sampling and Analysis Training Program and we believe it was the most successful course to date. The program has been running since 2010 and prior to this IASU's parent laboratory at Queens's University, (Analytical Services Unit) maintained on-site and off-site training programs for several years while participating in the DEW-line clean-up at Resolution Island. All of the training programs have been developed for Inuit and other residents of Nunavut to increase their understanding of contaminants in the arctic environment and to help prepare them for possible future employment in site remediation projects as well as environmental monitoring. The current course also introduced participants to laboratory practices that are defined by the ISO/IEC 17025 Standard that is used internationally by accredited laboratories. As part of our work in the IASU with the ArcticNet project,

Figure 8. Map of the sampling locations in the Apex River watershed. The West and East tributaries (WT, ET, respectively), the confluence (CF), and near the mouth of the river at Apex (AR).

hundreds of water samples were collected from local water sources by other ArcticNet researchers for metals analysis. These samples were available for Iqaluit based 'metals testing'. Preliminary testing of some samples was carried out using the AA at the Iqaluit laboratory (Figure 11). A selection of these samples (96) were ultimately shipped to the ASU at Queens University and analyzed using ICP-MS and ICP-OES techniques to determine a broad range of analytes and potential contaminants at extremely low concentrations.

Figure 9. Rebecca Edwards collecting PVC data in the Apex River watershed (photo by N. Liu).

Figure 10. Instrumentation for deriving the fraction of photosynthetically active radiation (FAPAR) - data logger (white box), PAR sensor looking down. These data are compared to another PAR sensor looking upward to collect total incident PAR. (photo by R. Edwards).

RESULTS

Cape Bounty Arctic Watershed Observatory (CBAWO)

Research results focused on several key areas of subsurface hydrology and related water quality indicators. Additionally, we completed major data compilations for lake water chemistry and obtained bathymetric and acoustic data from both lakes.

Results from a detailed water temperature survey of the West River were completed (Bolduc et al., submitted). These results demonstrate for the first time that thermal tracing in Arctic rivers can be used to identify subsurface and surface water inflows, a key first indication of the locations and seasonal dynamics of these phenomena. Water temperature surveys in the river show prominent temperature cooling events at locations where subsurface water inflows (Figure 12). This work was advanced in 2015 by the installation of a suite of river channel sensor systems and sampling wells for field investigations in 2016 and future years. This research will establish key linkages between slope and river water flows during baseflow, and will be critical for determining water quality impacts. This work complements efforts initiated at the Apex River in 2015.

Water quality measurements (pH, EC, dissolved organic carbon (DOC) concentration, dissolved total nitrogen, and $\delta^{13}C$) throughout the catchment show differences in water quality based on the water source as well as with proximity to disturbances from active layer detachments (ALDs). Radiocarbon dating also shows differences in the age of carbon suggesting potential inputs from permafrost-derived organic matter. For example, along the main channel, increases DOC concentration and $\delta^{13}C$ occur. This may be linked to the composition of the DOM and possible degradation or export through the watershed and into the West Lake. Analysis of organic matter

Figure 11. A) ASU research technician Sonja Koster, involved in the training of Inuit students; B) Students running water samples; C) Water Sampling at a nearby stream; D) Students of the 2015 season (left to right): Johnny Flaherty, Daniel Taukie and Will Autut.

using nuclear magnetic resonance spectroscopy and excitation-emission matrix spectroscopy will further elucidate the changes in water chemistry along the catchment, and from different water sources.

Results from a 2012 study of the seasonal changes in the composition of DOM across the subcatchments of the West watershed at the CBAWO indicates that both the seasonal hydrology, and the extent of disturbance and degree of surface runoff flowing through the disturbances, influences the composition of the DOM exported. DOM during snowmelt is typically the more degraded and becomes less degraded over the season. In contrast, other studies from arctic rivers show that the DOM is the most labile (fresher) during snowmelt (Holmes et al. 2008). The most extensively disturbed and channelized streams (PT and ALD) deliver the freshest DOM, while the less disturbed and channelized streams (GS and CR) deliver more degraded DOM (Figure 13).

Lake research generated several important results. Postdoctoral researcher A.Normandeau completed a comprehensive sidescan sonar and acoustic survey of both lakes, resulting in bathymetric and sedimentary structure data with unprecedented detail in the Arctic (Figure 14). This research has identified many submerged topographic features that will be used to evaluate groundwater seepage into the lakes in 2016.

In addition to carrying out lake water column profiling, we were also able to initiate a measurement program in the Headwater Lake of the West River. This lake was also sampled as part of the Hg contaminant research. Consolidation of the 2003-2015 lake hydrochemical record was completed and results indicate a sharp increase in many ions in the last few years (Figure 15). We are investigating possible mechanisms, but the results from both lakes indicate a similar pattern.

Concentrations of pCO_2 and pCH_4 were similar throughout most of the water column of East and West lakes, suggesting that these lakes are fairly well mixed during the open water season. However, in West Lake, concentrations of both of these greenhouse gases increase at 32 m just above the lake sediments, suggesting active microbial respiration in the sediments.

Terrestrial research focused on vegetation plots at the ITEX experimental site. Enhanced snowfall had the greatest impact on current year plant phenology and delayed the day of senescence by just over one week. The combination of enhanced snow and enhanced temperature had the greatest impact on the delay of senescence. Interestingly, our results indicate that even the plots furthest away from the snow fences experience some impact of increased snow deposition, suggesting that the without snow treatments may have been installed a bit too close to the snow fences – this will help with the design of future experiments of this type. Over the six year period, we observed a significant increase in plant vegetation cover (Figure 16), as well as a significant increase in plant diversity. The phenology of some species did not respond as much as others; *Salix arctica* in general showed little response to enhanced snow deposition. Overall our

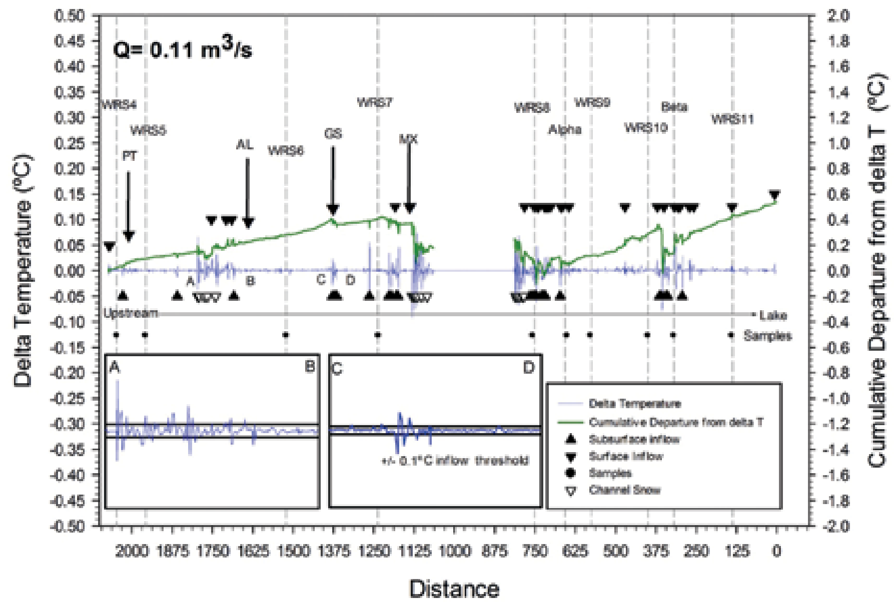

Figure 12. An example of a longitudinal temperature record from the West River on July 19, 2014. Temperature fluctuations indicate inflows from channel snow, and surface or subsurface sources.

results indicate a very strong response to changes in snowfall, and any changes in vegetation dynamics due simply to change in temperature appear to be offset in part by changes related to enhanced snowfall.

Apex River Watershed

The hydrological monitoring of the Apex River watershed clearly indicates that the vast majority of the water contributing to the Apex River outflow (AR) is derived from the West tributary (WT, ~75%), and that the East tributary (ET) contribute only approximately 18% of the runoff measured at the Apex site (AR) (Figure 17). All stream gauging locations show very rapid response to rainfall events (Environment Canada, 2015).

Analyses of the dissolved metals, ion concentrations, DOM fluorescence and stable isotope results from 2015 are still on going. However results of the DOC concentrations indicate the typical strong seasonal trends in these parameters over the runoff period, though minimal variability across sampling sites (Figure 18).

Geostatistical analysis of ARW snow survey data (from both broad scale and intensive sampling survey efforts) was conducted to improve our understanding of the spatial structure of snow distribution in this topographically complex terrain. These data were subsequently used to develop a model of terrain and wind-based snow-redistribution (Figure 19 and 20). Without *a priori* knowledge of the optimal landscape stratification scheme, we found the depositional areas to be under-represented within the sampling data. Nevertheless, the results from our first year of sampling demonstrate that these important depositional areas represent less than 10% of the landscape, but may contain >20% of the basin wide SWE. We also observed similar or higher snow storage in valley-bottom areas and subsequent surveys will need to target these areas to improve landscape SWE estimates, since they were strongly under-represented in the snow surveys.

Surface profiling of natural groundwater tracers (temperature; electrical conductivity) revealed local anomalies and reach scale variations indicative of subsurface flows to the channel (Figure 21). Field

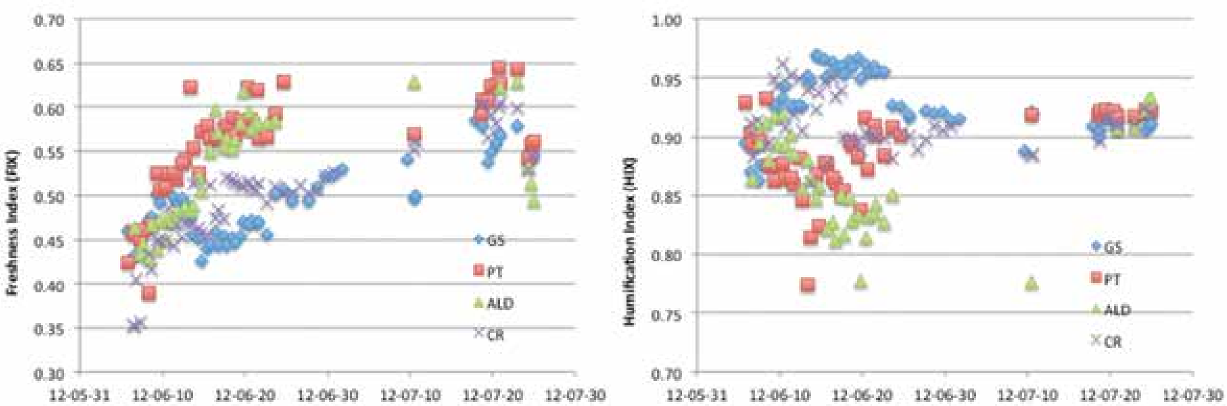

Figure 13. Seasonal trends in DOM fluorescence in the subcatchments at CBAWO. The FIX indicates the relative freshness of the DOM (higher FIX is less degraded). FIX the emission intensity at 380 nm divided by the maximum intensity between 420 and 435 nm at an excitation of 310 nm. HIX indicates the relative degree of humification, and is calculated as the area under the emission spectra from 435-480 nm divided by the sum of the peak areas at 300-345 nm and 435-480 nm, for excitation at 254 nm (Fellman et al., 2010).

work included ground truthing of a detailed surficial geology map of the study area derived from air-photo interpretation. Terrain analysis will be conducted to interpret the results of our local scale mapping of natural groundwater tracers in relation to detailed knowledge of surficial deposits and topography. Groundwater monitoring was conducted in three different hillslope-riparian-stream sequences, where groundwater seepage was observed. At one of the three sites we observed a relatively rapid change in water levels possibility related to dynamics between subsurface flownets and frost table degradation.

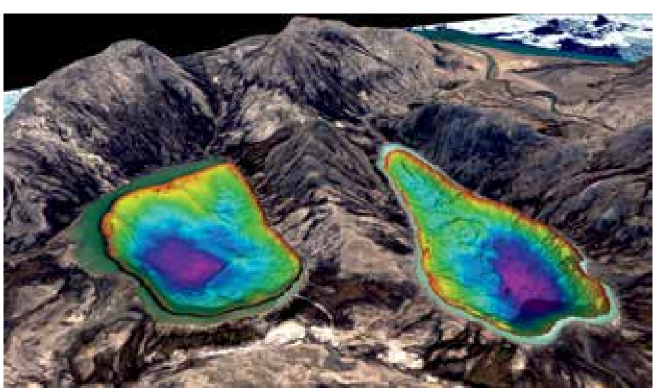

Figure 14. An image of the bathymetry of the East (left) and West (right) lake bathymetry obtained from the 2015 surveys at CBAWO.

Total coliforms in the Apex River were present in all 61 samples tested, at densities ranging from 3.1 to 770 colony forming units (cfu) / 100ml. *E. coli* was detected in only five samples, at very low densities ranging from 1 to 5.5 cfu/100ml. Coliforms and *E. coli* were detected across water temperatures ranging from 0.1 to 15.5 °C. Interestingly, the largest concentrations of *E. coli* and total coliforms was measured at very low water temperatures (<2°C for *E. coli* and <1°C for total coliforms). We are still evaluating the dataset to determine seasonal trend and relate bacteria concentrations to other environmental controls.

In our terrestrial research program we are now: 1) classifying vegetation communities for the ARW using contemporary WorldView-3 data collected in 2015; 2) examining the relationship between field measurements of Percent Vegetation Cover (PVC) and normalized difference spectral indices (NDSIs) derived from the WorldView-3 data for the ARW using linear regression analysis (Figure 22); 3) deriving Landsat normalized difference vegetation index (NDVI) time series for the ARW to quantify overall trends in 'greenness' derived for different vegetation communities from 1985-2015; and 4) comparing NDVI trends and rates of change for the ARW to explain their relationships in the context of other climate variables.

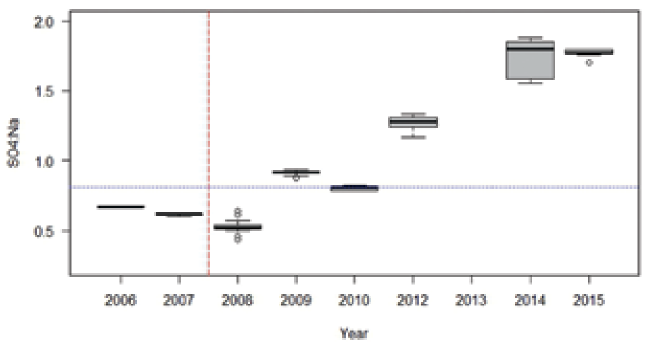

Figure 15. The long term record of chemical change in West Lake. Note the increase in SO_4:Na since 2010, several years after the landscape disturbance that occurred at the end of the 2007 runoff period.

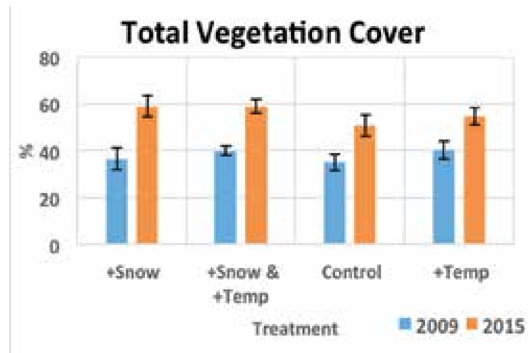

Figure 16. Changes in vegetation cover over six years in the different treatments.

We have generated a classified image and NDSI data for the ARW. For instance, NDVI data are being examined to determine their relationship with field measures. The PVC determined using the ITEX method has a significant relationship to the satellite-derived NDVI from the WorldView-2 data (p=0.0008) and a relatively high correlation (Figure 22; r^2 = 0.61). With a strong significant relationship between satellite-derived NDVI and PVC it is possible to generate a model and interpolate PVC for the rest of the watershed based on high spatial resolution satellite data.

DISCUSSION

Collectively, our research programs are identifying key themes related to water security in a changing Arctic climate. Aside from changes in water availability from changing snow and rainfall, our work has increasingly focused on the last runoff period in July-October, a time when water availability is diminished and where water quality impacts appear to be most pronounced. Our work has shown the significant role subsurface water contributions play in sustaining late season flow, a key time for water availability for communities, particularly Iqaluit.

To date, our work has identified significant differences in the water chemistry in the West River at Cape Bounty. This river has been impacted by fluxes of carbon and possibly other materials from active layer detachments (Grewer et al., 2015), but previous work has not examined the composition of DOM in combination with conventional water quality indicators to establish possible shifts in biogeochemistry. Once organic geochemical analyses are complete, a holistic picture of climate-induced changes on water quality will ensue. This will subsequently improve the

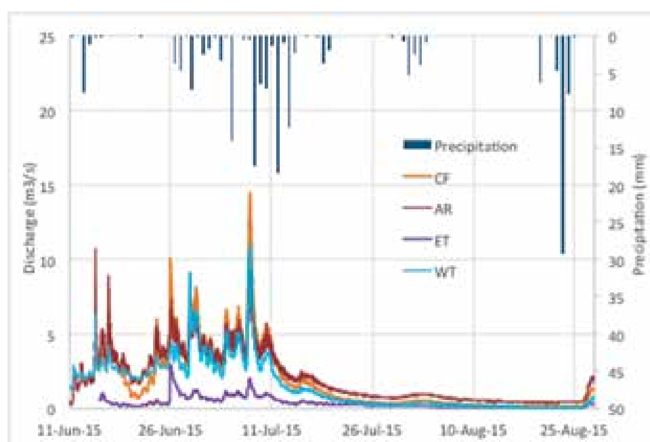

Figure 17. Stream discharge hydrographs for the gauging sites along the Apex River, and total daily precipitation as recorded by the Environment Canada weather station in Iqaluit.

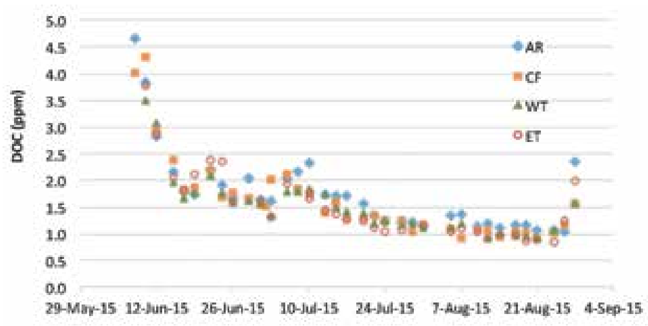

Figure 18. Dissolved organic carbon concentrations at the four sampling sites along the Apex River.

fundamental understanding of how permafrost thaw and active layer detachments alter the water quality of Arctic ecosystems.

The lakes at CBAWO have shown a remarkable amount of hydrochemical change in the past few years. While the mechanisms for these changes are not fully understood, the rate and timing of change is inconsistent with the earlier period of permafrost slope disturbance in 2007. Hence, we suspect a mechanism within the lakes. The physical and chemical changes are matched by relatively stable conditions in other major lake indicators. For example, concentrations of both CO_2 and CH_4 are low in the surface waters of East and West lakes, resulting in their net exchange with the atmosphere also being low.

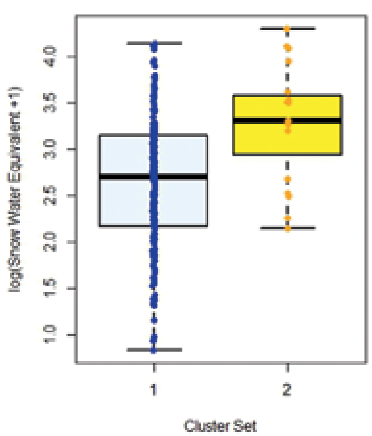

Figure 19. Snow water equivalent in erosional (left) vs depositional (right) landscape units.

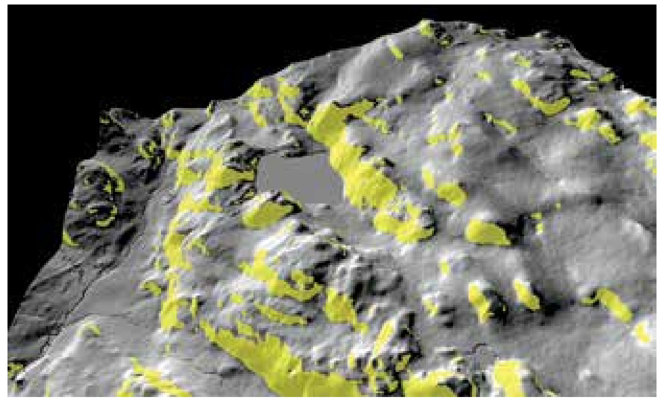

Figure 20. Landscape clusters showing snow depositional areas (yellow) and erosional areas (remaining areas). Additional stratified sampling will be required in subsequent years to improve estimates of snow storage in deep valley bottom areas.

At the Apex River, our first year findings confirm very high variability in end-of-season snow distribution in the topographically complex Apex River watershed due to wind redistribution (vegetation effects are negligible due to the lack of shrubs or trees in this environment). This variability makes it difficult to accurately estimate basin-wide average SWE. Conversely, terrain-based stratification shows potential as a way to improve sampling efficiency and/or improve confidence intervals for future snow surveys. Accurate basin-wide estimates of snow water equivalent are a crucial step towards improving our understanding of water balance terms in the Apex River watershed and will be used in subsequent snowmelt and streamflow modelling exercises. By calibrating numerical hydrology models to both precipitation inputs (from snow surveys and rain gauge records) and available streamflow records for the watershed, we will develop reliable estimates of the partitioning of end of winter SWE into meltwater and evaporation/sublimation components and their sensitivity to climate.

Groundwater inputs to surface waters support critical ecological functions in streams and lakes. Groundwater discharge (baseflow) provides a buffering mechanism for natural variations in storm

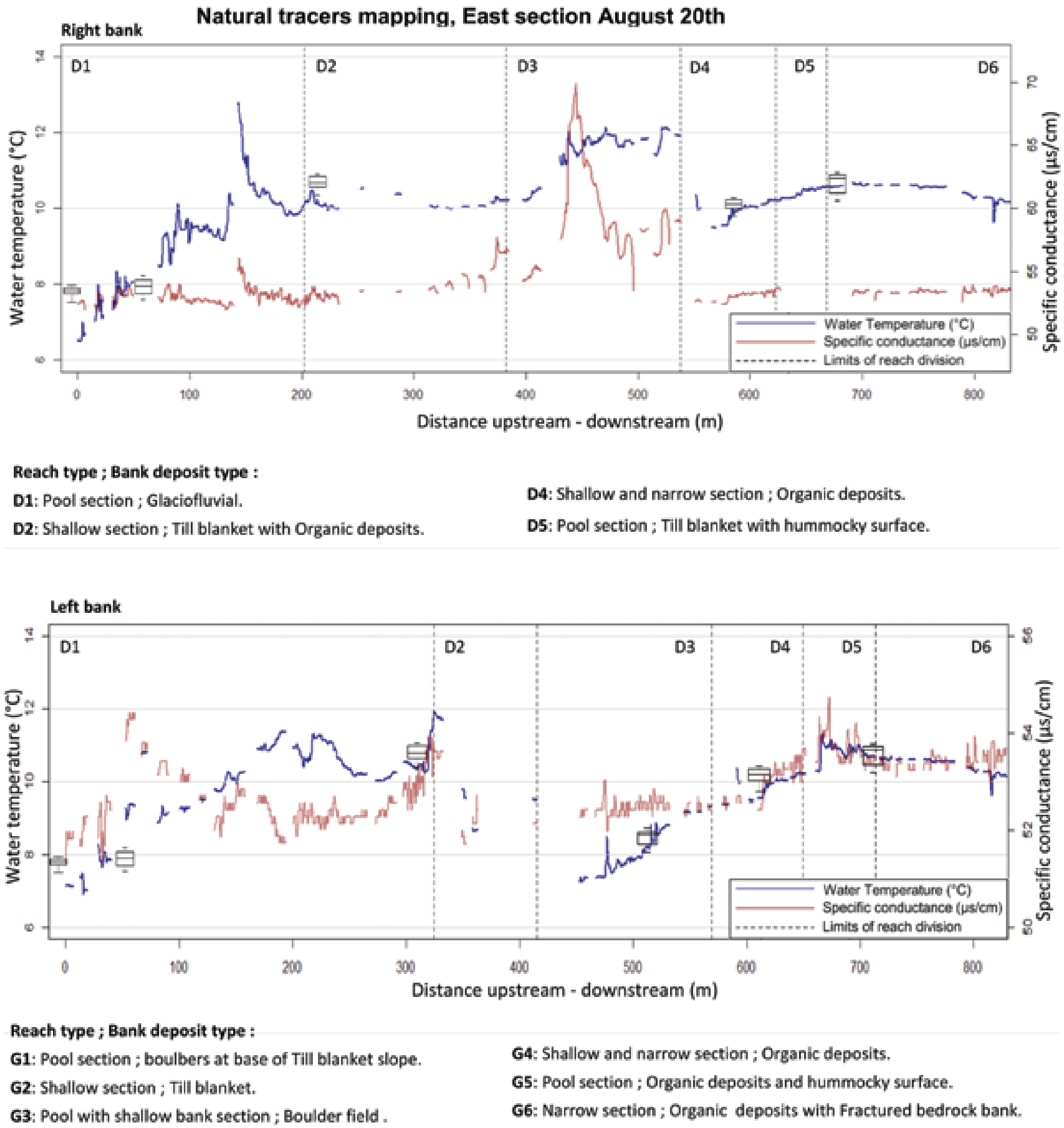

Figure 21. Results of temperature and specific conductance profiling. Surface water parameters measured along banks of the East Section on August 7th, 2015; boxplots show the distribution of temperatures recorded during tracer mapping. Reaches with distinct channel and/or bank characteristics are delineated (vertical dashed lines); see text below the figure for descriptions.

flow. Groundwater also exerts a strong local influence on the physical and chemical characteristics of surface waters, and thereby on the specific habitats and life histories of aquatic organisms. Yet in most catchments (including the Apex River) the local-scale distribution of groundwater fluxes to surface waters is unknown. This lack of knowledge was highlighted by the Intergovernmental Panel on Climate Change (IPCC) as a key limitation for assessing climate change impacts on aquatic ecosystems. This issue is particularly relevant for northern catchments where permafrost degradation is expected to significantly impact

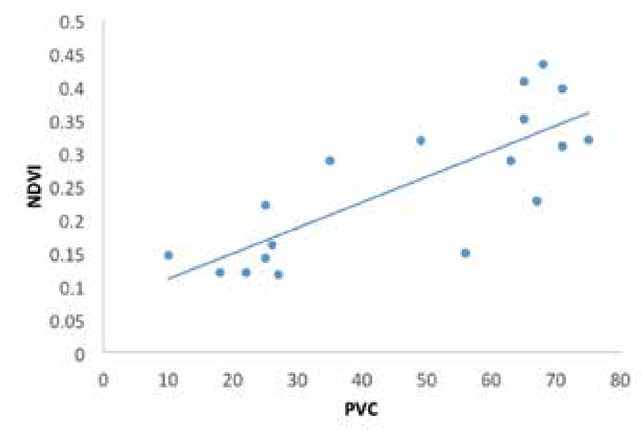

Figure 22. The relationship between percent vegetation cover (PVC) and NDVI (derived from WorldView-2 data) determined using the ITEX method (r^2= 0.61).

hydrological processes. The dearth of knowledge about local groundwater fluxes to surface waters is equally limiting for ecosystem approaches to water resources management. Thus, the outcome of this research is also relevant to the management of northern water resources, where for example the City of Iqaluit has recently proposed drawing water from the Apex River to meet future needs.

Microbial pathogens represent the most significant threat to human health from drinking water. Public Health authorities rely on indicator bacteria (typically total coliforms and *E. coli*) as surrogates for microbe pathogens in drinking water, which are costly and difficult to enumerate accurately and reliably. Total coliforms and *Escherichia coli* (a subset of the coliforms), which are detected quickly and easily, are the standard indicator bacteria utilized for sanitary water analysis in Canada (Health Canada 2014). NRI has conducted routine monitoring of indicator bacteria in the Apex River since 2009; and our unique long term dataset on the river's microbial condition will be valuable to the City of Iqaluit as it finalizes engineering designs to utilize the Apex River as a secondary potable water supply for the City.

Enhanced snowfall can have a range of impacts on Arctic ecosystems and water security. When deep enough, enhanced snow can lead to an increase in soil temperatures, influencing active layer development and winter respiration rates. This increase in temperatures might lead to increased rates of soil carbon loss. Our results suggest that an additional impact of enhanced snowfall is an increase in plant growth, as seen in the six year results from our ITEX experiment. This increase in plant growth could help offset soil carbon losses due to the direct impacts of enhanced snowfall on soil carbon dynamics. The dynamics of soil organic matter formation and decay can ultimately influence water quality, as soil organic matter plays a key role in the cycling of many elements that also contribute to water quality metrics.

Given summer mean temperatures are near freezing in the Canadian High Arctic, a few degree 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). My research examines the response of terrestrial ecosystems at high latitudes to warming. This research is extremely important, as these ecosystems are highly sensitive to warming, yet it remains unclear as to how these ecosystems will respond from a productivity perspective but also with respect to biospheric feedbacks to global climate (Bonan et al., 1995).

Collecting *in situ* measurements of biophysical 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. We have demonstrated this at local scale and at high spatial resolutions. Deriving biophysical measurements from remote sensing data is the only feasible method to examine 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 remote sensing spectral indices 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 help us develop adaptation strategies for communities and resource industries living and operating in Canada's North.

CONCLUSION

The first year of this project was highly successful. We made substantial research accomplishments and integrated a number of new researchers into our teams. Additionally, we have developed strong collaborative and cooperative relationships with NRI and the Iqaluit community, to develop relevant research questions and capacity to ensure water security for northerners. We have continued to engage a large team of students, postdoctoral researchers and technicians in our research programs, and have recruited a large cohort of students for 2016 project work. This level of activity promises to continue to advancing both our network goals to contribute to knowledge transfer to northern stakeholders, and to deliver high quality research.

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Providing Climate Scenarios for the Canadian Arctic with Improved Post-Processing Methods

Project Leader

Alain Mailhot (Institut national de la recherche scientifique - Eau, Terre et Environnement)

Network Investigator

Diane Chaumont (Ouranos)

Collaborators

Carl Barrette (Université Laval)
Ross Brown (Ouranos)
Dany Dumont (Institut des sciences de la mer de Rimouski)
Patrick Grenier (Ouranos)
Mickaël Lemay (ArcticNet Inc.)
Simon Senneville (Université du Québec à Rimouski)

HQP

Emilia Paula Diaconescu, Post-Doctoral Fellow (Institut national de la recherche scientifique - Eau, Terre et Environnement)
Guillaume Talbot, Research Associate (Institut national de la recherche scientifique - Eau, Terre et Environnement)

ABSTRACT

Planning and adapting to a warming Arctic require the best information on the possible climate change over the next several decades. This information is typically obtained from physically-based models of the Earth climate system which simulate its response to increasing greenhouse gas concentrations. Usually a large number of model simulations are needed to take account of different greenhouse gas emission scenarios, of differences in model physics formulations and of the natural variability of the climate system. While climate scientists have high confidence in the projected global-average range of warming, there is greater uncertainty in regional and local changes relevant for decision-makers, particularly in the Arctic region where natural components such as sea ice and permafrost exist. One limitation comes from the resolution of the models. For example, the highest resolution for model simulations currently available for the Arctic region is ~ 25 km, a scale still too coarse to capture many of the important local-scale influences on climate. For this and other reasons, climate simulations must be post-processed, i.e. downscaled and statistically adjusted to obtain statistical properties similar to those of observed time series. The objective of this project is to provide the Canadian Arctic decision-makers and communities with scenarios for temperature, precipitation, wind speed and other climatic variables and indicators. The state-of-the-art post-processing methods employed aim at correctly representing extreme weather events and take into account observational uncertainties as well as inter-variable correlations. Wind scenarios, a major development of this project, are used notably for assessing climate change impacts on sea ice regimes and coastal erosion. The project also includes active linkages to several ArcticNet proposals addressing climate change impacts on Arctic ecosystems and hydrology.

KEY MESSAGES

- Providing climate information in the Canadian Arctic is a challenge due to sparse observing networks and short records.
- Climate change is expected to seriously impact the Canadian Arctic.
- It is therefore crucial to adequately describe the historical climate of the Canadian Arctic and to develop projections of future changes for climatological indices used in impact and adaptation studies.
- Special attention should be devoted to the future evolution of extreme weather events in the Canadian Arctic considering the impact they can have on local communities and infrastructures.
- Reanalysis and gridded datasets are valuable complementary datasets that can be used to assess historical Canadian Arctic climate.
- Large differences in historical climate are reported when reanalyses are compared as well as large range in the magnitude and timing of the simulated climate change signal in the Arctic due to the complexity of processes and feedbacks involved in climate models.
- Post-processing, namely the design of climate scenarios by merging observed and simulated information, is essential to develop projections that meet the needs of users at the Arctic community level.
- The project's main goal is to provide ArcticNet Integrated Regional Impact Studies (IRIS) related projects with climate scenarios that benefit from state-of-the-art post-processing methods.
- Basic scenarios (daily time series for 2-meter mean, minimal and maximal temperatures, precipitation, and 10-meter horizontal wind), covering specific sub-periods within the 1950-2100 period, as well as specific indices (e.g. number of freeze-thaw cycles, total annual solid

precipitation, growing degree-days, etc.) will be developed.

- Datasets (observations, interpolated, reanalysis, and climate simulations) have been gathered and indices have been defined to characterize the Arctic climate in historical and future climates.
- Basic scenarios will be used for a pilot study on wave and fast ice dynamics in Baffin Bay and Hudson Bay and for contributing to upcoming IRIS reports.
- The interdependence (correlation) between temperature and precipitation series is important in the Arctic (especially for winter), and climate scenarios should be constructed with methods that conserve this statistical property.

OBJECTIVES

Project objectives are organized into: 1) upstream objectives (directly oriented at improving methods for designing basic scenarios); 2) basic scenarios development; and 3) downstream objectives (application of basic scenarios and derived climate indicators). More specifically, the objectives are:

1. Upstream objectives:
    a. Inventory and acquisition of available observational products for wind speed, and assessment of selected post-processing methods
    b. Development of post-processing methods that consider observational uncertainty
    c. Assessment of multivariate post-processing methods
2. Basic scenarios development:
    a. Synthesis of upstream methodological results and development of basic scenarios
    b. Assessment and characterization of daily extremes in observational products, simulations and scenarios
3. Downstream objectives
    a. Modeling of wave and fast ice dynamics in Baffin Bay and Hudson Bay
    b. Provision of climate indicators and analysis for the IRIS-4 report and elaboration of the climate chapter.

INTRODUCTION

Impacts of climate change are already observed in the Canadian Arctic. As these changes have huge impacts and are expected to increase in the near future, it is important to have access to reliable projections in order for Arctic communities to develop efficient adaptation measures. However, the range in the magnitude and timing of the simulated climate change signal in the Arctic is large due to the complexity of processes and feedbacks involved in climate models, making it difficult to develop reliable projections over this region. For example, sea ice cover, snow and ice albedo feedbacks, surface temperature inversions and permafrost are key components of the Arctic climate system that are not well-simulated by even the more advanced global and regional climate models. Characterization of the current climate in the Arctic is also more difficult than for mid-latitudes due to sparse observing networks, short periods of record, and large differences in historical climate based on available reanalyses and gridded datasets (Eum et al. 2014; Rapaic et al. 2015).

As a consequence, post-processing, namely the design of climate scenarios by merging observed and simulated information, is essential. Post-processing (also often referred to as “statistical adjustment”) consists of both downscaling and bias-correction of climate simulations (Gennaretti et al. 2015). Post-processing is necessary to develop climate projections that meet the needs of users of the Arctic community.

The main goal of this project is to provide ArcticNet IRIS related projects with climate scenarios that benefit from state-of-the- art post-processing methods. Improvements (relative to previous IRIS scenarios) include the use of new simulation results from regional models, coverage of marine areas, consideration of the observational uncertainty in the post-processing, and the development of scenarios for wind speed. Special attention will be devoted to extremes in precipitation and temperature as well as to inter-variable dependences. Production of time series, called basic scenarios, for 2-meter mean, minimal and maximal temperatures (Tmean, Tmin and Tmax), precipitation (Pr), and 10-meter horizontal wind (Vx,y) covering specific periods within the 1950-2100 will be produced.

Basic scenarios will be used for a pilot study on wave and fast ice dynamics in Baffin Bay and Hudson Bay and for climate indicators required by IRIS reports. The pilot study, led by Prof. Dany Dumont, is motivated by the following sets of results: As reported by Senneville and St-Onge-Drouin (2013), the maximum volume of ice reached during winter in Hudson Bay is expected to decrease by 20% in a future climate for the period 2041-2070, which represents a loss of 376 km^3, and the ice-covered season will on average be shorter by 39 days. Moreover, the same study revealed that the length of the period during which the coast is covered with landfast ice will shortened by 17 to 42 days at three coastal communities of Nunavik, namely Quaqtaq, Umiujaq and Kuujjuaq. This numerical modeling study, sponsored by Transport Québec, provides a strong motivation for pursuing research in order to better quantify the impacts of these changes on the coast. Waves are a powerful agent of coastal erosion. The ice spatial distribution influences how much energy is transferred from wind to waves (e.g. Thompson and Rogers 2014), which can have a destructive impact on sea ice (e.g. Dumont et al. 2011). Nonetheless, it is only recently that wave-ice interactions and landfast ice dynamics (Lemieux et al. 2015) have been included in numerical models, such that the most recent impact studies of coastal erosion in ice-covered environments, if any, do not take into account these very important effects.

ACTIVITIES

Preliminary work and analysis

- Datasets (including ground stations, measurements from ships, interpolated series, reanalyses, and climate simulations) relevant for the project have been identified and collected.
- The time periods covered by the various datasets were compared to identify the appropriate historical and future periods considered in the forthcoming analysis.
- The spatial coverage of the various datasets was compared with the IRIS regions to select the most appropriate datasets to be used for the forthcoming analysis.
- Trend analyses of annual precipitation and mean annual temperature series were performed over the historical period (1950-2005) for AHCCD, NRCan and CORDEX simulations using the two Canadian RCM climate models (CanRCM4 and CRCM5). Mann-Kendall Test and the Theil-Sen Trend Line Slope were used. (See Table 1 for definition of dataset acronyms.)

Other activities are reported for each of the sub-objectives listed in the Objectives section:

Univariate wind speed post-processing

Inventory and acquisition of available observational products for wind speed.

- The ERA-interim and CFSR re-analyses as well as marine (ICOADS) and land station climate data (see Table 1) have been analyzed for a domain covering Hudson Bay, Baffin Island, and surrounding water areas. An intercomparison was carried out of hourly wind data at nine coastal stations and ICOADS marine data. The following metrics have been used for the comparison of these series: RMSE (root mean squared error), correlation coefficient, trends, and wind rose.

Table 1. List of datasets gathered for the project.

Dataset name	Type	References
Adjusted and Homogenized Canadian Climate Data (AHCCD)	Meteorological station records	Vincent et al. (2012) Mekis and Vincent (2011)
DAI Portal and Ministère du Développement Durable, de l'Environnement et de la Lutte contre les Changements Climatiques (MDDLCC) datasets	Meteorological station records	
NRCan gridded-dataset (10 km)	Interpolated precipitation	McKenney et al. (2011)
Climate Forecast System Reanalysis (CFSR)	Reanalysis	Saha et al. (2010)
European Center for Medium-Range Weather Forecast Reanalysis (ERA-Interim)	Reanalysis	Dee et al. (2011)
Japanese 55-year Reanalysis (JRA-55)	Reanalysis	Kobayashi et al. (2015)
Modern-Era Retrospective Analysis for Research and Applications Reanalysis (MERRA)	Reanalysis	Rienecker et al. (2011)
Global Meteorological Forcing Dataset for Land Surface Modeling (GMFD)	Reanalysis	Sheffield et al. (2006)
International Comprehensive Ocean-Atmosphere Data Set (ICOADS)	In situ measurements by ships	Woodruff et al. (2011)

Assessment and evaluation of selected wind post-processing methods.

- Post-processing methods for wind scenarios are currently under investigation.
- M.Sc. student (M.N. Abgazo) has been recruited to work on this topic. He will start working on the project once he has completed his mandatory first-year courses at UQAM in May 2016.
- A literature review has been initiated related to scenario construction principles for wind variables and in conditions with sparse observations to ensure the M.Sc. student can quickly get up to speed next summer.

Consideration of observational uncertainty (OU) in post-processing

Development of the method is based on previous assessments of OU:

- Discussions have taken place with collaborators to refine the objectives and methodology for this research theme.
- Comparisons of temperature and precipitation series from the various datasets are underway to better characterize the differences between available datasets in assessing the historical climate of Arctic.
- M.Sc. student (Alexis Pérez-Bello) has been recruited for this research subject. He started in October as an internship student and is a full master's degree student at INRS since January 2016.

Comparison of OU uncertainty with other uncertainties:

- Work planned for Year 2 of the project.

Assessment of multivariate post-processing methods

Assessment of multivariate post-processing methods (precipitation vs temperature):

- An in-depth study of the temperature-precipitation time series interdependence as well as the design of a method for constructing climate scenarios that preserves interdependence structure has been conducted.

- A paper has been published in a peer-reviewed journal (Gennaretti et al. 2015).

Assessment of multivariate methods for Vx,y vs. T, considering results for Pr vs. T and of obj. 1a:

- Work planned for Year 2 of the project.

Synthesis of upstream methodological results and development of basic scenarios

Development of improved post-processing methods based on results from upstream objectives and obj. 2b:

- Work planned for Year 2 of the project.

Development of basic scenarios:

- Work planned for Year 3 of the project.

Assessment and characterization of extremes

Project activities for this objective are divided into two parts: 1) analysis of daily extremes over the historical period (1950-2005) in observations, reanalyses, and historical simulations; 2) analysis of projections according to two scenarios (RCP 4.5 and RCP 8.5) for the 2005-2100 period. Only activities related to the first objective were realized during the first year of the project.

- Indices to be used for the project were identified.
- Ten daily precipitation indices were computed (PRmean, PR1mm, RX1day, RX5day, P95, P99, No_p95, No_p99, R95ptot, R99ptot) for all CORDEX historical simulations, reanalyses and gridded dataset on their native grid. For stations, annual index series were computed for each valid year from 1950 to 2005 (see Table 3 for definition of indices).
- A first comparative analysis of simulations and reanalyses with station records and gridded datasets was realized over the Arctic region encompassing the IRIS 1 and IRIS 2 sub-regions. The comparison was carried out at Canadian stations located north of the 62°N parallel by selecting the closest grid point from reanalyses and CORDEX-ARCTIC historical simulations. Time series of regional mean values and spatial distribution of the climate mean over the reference period (1980-2004) were also compared.
- Several performance metrics were computed: mean bias, correlation and root mean squared difference (RMSD). For climate means, only stations with at least 15 valid years during the reference period were considered.

Assessment of upstream method results in terms of extremes:

- Work planned for Year 2 of the project.

Estimation of changes in Pr and T extremes in the basic scenarios:

- Work planned for Year 3 of the project.

Modeling of wave and fast ice dynamics in Baffin Bay and Hudson Bay

Set-up of the WAVEWATCH III model and gathering of sea ice and wave data for input and validation:

- Latest parameterizations of wave attenuation and wave-induced ice breaking (Williams et al. 2013a,b) were incorporated into the WAVEWATCH III spectral wave model (WW3, Tolman 2014) and tested.
- A one-year simulation using sea ice fields produced by ISMER’s Hudson Bay model (Saucier et al. 2004, Senneville and St-Onge-Drouin 2013) was also produced.

Implementation of the landfast ice module and development of the wave-ice coupling interface:

- Work planned for Year 2 of the project.

Validation of the models and realization of the future climate ensemble using climate scenarios from obj. 2a:

- Work planned for Year 3 of the project.

Climate indicators for upcoming IRIS reports and ArcticNet projects

IRIS-4 Update Report - Climate chapter:

- A draft outline for the Climate Chapter and list of potential contributing authors was developed in the fall of 2015 and submitted to the Report editors.
- An initial list of climate indicators was distributed to the IRIS-4 Update Report chapter authors and to the project in early December 2015.

RESULTS

The first year was essentially devoted to the acquisition of datasets and preliminary analysis and comparison of these datasets. The following paragraph present some preliminary results for each research objective listed above:

Preliminary analysis of available datasets

- The reference period of 25 years (1980-2004) was selected as the common period between available simulations and reanalyses, three of the reanalyses having records starting in 1979.
- For the future climate, three 25-year time periods were identified: 2025-2050 (close future), 2050-2075 (mid-future), 2075-2100 (far-future).
- Table 1 gives the list of reanalyses, interpolated, observational datasets gathered for the project.
- Table 2 gives the list of CORDEX simulations with their characteristics gathered for the project.

Univariate wind speed post-processing

- ERA-interim (0.75 deg and 6h horizontal and temporal resolution, respectively) and CFSR (0.31 deg and 1h) have relatively small differences in terms of zonal and meridional wind speed over the area.
- None of the two reanalysis systematically outperforms the other.
- CFSR will hence be selected for subsequent steps because of its convenient higher spatio-temporal resolution.
- A limitation with ICOADS data (ship measurement) is that data are very sparse in presence of the sea-ice cover.

Consideration of observational uncertainty (OU) in post-processing

- A more detailed working plan has been defined for this part of the project.
- This research objective will focus on the sensitivity of the scenarios to the reference dataset used in the post-processing. It will also investigate how the various reference datasets could be combined in the post-treatment procedure.
- This research objective will hereafter be called ‘Sensitivity of scenarios to reference datasets and development of scenarios combining different reference datasets’.

Table 2. List of CORDEX simulations gathered for the project.

Regional Climate Model-Simulation domain	Driving fields (GCM or reanalysis)	Period (RCP)	Number of simulations
CanRCM4-CORDEX-ARCTIC	CCCma-CanESM2	1951-2005 (Historical)	2
	CCCma-CanESM2	2006-2100 (RCP 4.5)	2
	CCCma-CanESM2	2006-2100 (RCP 8.5)	2
	ERA-Interim	1989-2009 (Evaluation)	2
RCA4-CORDEX-ARTIC	CCCma-CanESM2	1951-2005 (Historical)	1
	CCCma-CanESM2	2006-2100 (RCP 4.5)	1
	CCCma-CanESM2	2006-2100 (RCP 8.5)	1
	ICHEC-EC-EARTH	1951-2005 (Historical)	2
	ICHEC-EC-EARTH	2006-2100 (RCP 4.5)	1
	ICHEC-EC-EARTH	2006-2100 (RCP 8.5)	2
	MPI-M-MPI-ESM-LR	1951-2005 (Historical)	2
	MPI-M-MPI-ESM-LR	2006-2100 (RCP 4.5)	1
	MPI-M-MPI-ESM-LR	2006-2100 (RCP 8.5)	2
	NCC-NorESM1-M	1951-2005 (Historical)	1
	NCC-NorESM1-M	2006-2100 (RCP 4.5)	1
	NCC-NorESM1-M	2006-2100 (RCP 8.5)	1
	ERA-Interim	1980-2010 (Evaluation)	2
CRCM5-CORDEX-ARCTIC	ERA-Interim	1958-2012 (Evaluation)	1
	MPI-M-MPI-ESM-LR	1949-2005 (Historical)	1
	MPI-M-MPI-ESM-LR	2006-2100 (RCP 8.5)	1
CanRCM4-CORDEX-NA	CCCma-CanESM2	1951-2005 (Historical)	2
	CCCma-CanESM2	2006-2100 (RCP 4.5)	2
	CCCma-CanESM2	2006-2100 (RCP 8.5)	2
	ERA-Interim	1989-2009 (Evaluation)	2
RCA4-CORDEX-NA	CCCma-CanESM2	1951-2005 (Historical)	1
	CCCma-CanESM2	2006-2100 (RCP 4.5)	1
	CCCma-CanESM2	2006-2100 (RCP 8.5)	1
	ICHEC-EC-EARTH	1951-2005 (Historical)	1
	ICHEC-EC-EARTH	2006-2100 (RCP 4.5)	1
	ICHEC-EC-EARTH	2006-2100 (RCP 8.5)	1
	ERA-Interim	1980-2012 (Evaluation)	1
HIRHAM5-CORDEX-NA	ICHEC-EC-EARTH	1951-2005 (Historical)	1
	ICHEC-EC-EARTH	2006-2100 (RCP 4.5)	1
	ICHEC-EC-EARTH	2006-2100 (RCP 8.5)	1
	ERA-Interim	1989-2009 (Evaluation)	1
CRCM5-CORDEX-NA	CCCma-CanESM2	1951-2005 (Historical)	1
	CCCma-CanESM2	2006-2100 (RCP 4.5)	1
	MPI-M-MPI-ESM-LR	1951-2005 (Historical)	1
	MPI-M-MPI-ESM-LR	2006-2100 (RCP 4.5)	1
	ERA-Interim	1979-2012 (Evaluation)	1

Table 3. Selected precipitation and temperature indices (a complete description of these indices can be found in Klein Tank et al. 2009).

Label	Description
PRmean	Annual mean of daily precipitation
PR1mm	Number of wet days (annual number of days with daily precipitation > 1mm/day)
RX1day	Annual maximum 1-day precipitation amount
RX5day	Annual maximum 5-day precipitation amount
P95	95th percentile of wet-day precipitation over the reference period
P99	99th percentile of wet-day precipitation over the reference period
No_p95	Frequency/number of very wet days (annual frequency/number of days with daily precipitation > P95)
No_p99	Frequency/number of extremely wet days (annual frequency/number of days with daily precipitation > P99)
FD	Frost days (annual number of days with daily minimum temperature< 0° C)
ID	Ice days (annual number of days with daily maximum temperature < 0° C)
TNn	Annual minimum value of daily minimum temperature
TXn	Annual minimum value of daily maximum temperature
TNx	Annual maximum value of daily minimum temperature
TXx	Annual maximum value of daily maximum temperature
SU15	Arctic summer days (annual number of days with daily maximum temperature > 15° C)
TR10	Artic summer nights (annual number of days with daily minimum temperature > 10° C)
HDD17	Heating degree days (annual sum of daily mean air temperature degree days below 17° C)
CDD18	Cooling degree days (annual sum of daily mean air temperature degree days above 18° C)
GDD5	Growing degree days (annual sum of daily mean air temperature degree days above 5° C)
TNstd	Standard deviation of daily minimum temperature over the reference period
TXstd	Standard deviation of daily maximum temperature over the reference period
TN10	10th percentile of daily minimum temperature over the reference period
TX10	10th percentile of daily maximum temperature over the reference period
TN90	90th percentile of daily minimum temperature over the reference period
TX90	90th percentile of daily maximum temperature over the reference period
TN10p	Cool nights (annual percentage of time when daily minimum temperature is < 10th percentile of daily minimum temperature over the reference period)
TX10p	Cool days (annual percentage of time when daily maximum temperature is < 10th percentile of daily maximum temperature over the reference period)
TN90p	Warm nights (annual percentage of time when daily minimum temperature is > 90th percentile of daily minimum temperature over the reference period)
TX90p	Warm days (annual percentage of time when daily maximum temperature is > 90th percentile of daily maximum temperature over the reference period)

Assessment of multivariate post-processing methods

- The interdependence between climatic variables should be taken into account when developing climate scenarios. For example, temperature-precipitation interdependence in the Arctic is strong and impacts other physical characteristics, such as the extent and duration of snow cover. However, this interdependence is often misrepresented in climate simulations.
- Two two-dimensional (2-D) methods for statistically adjusting climate model simulations to develop plausible local daily temperature (Tmean) and precipitation (Pr) scenarios were used.
- The first 2-D method is based on empirical quantile mapping (2Dqm) and the second on parametric copula models (2Dcopula).
- Both methods were improved by forcing the preservation of the modeled long-term warming trend and by using moving windows to obtain an adjustment specific to each day of the year.
- These methods were applied to a representative set of 13 global climate model simulations at 26 Canadian Arctic coastal sites and tested using an innovative cross-validation approach.
- Intervariable dependence was evaluated using correlation coefficients and empirical copula density plots.

- These 2-D methods, especially 2Dqm, adjusted individual distributions of climatic time series as well as a common one-dimensional method (1Dqm). Furthermore, although 2Dqm outperformed the other methods in reproducing the observed temperature-precipitation interdependence over the calibration period, both 2Dqm and 2Dcopula performed similarly over the validation periods.
- For cases where temperature-precipitation interdependence is important (e.g., characterizing extreme events and the extent and duration of snow cover), both 2-D methods are good options for producing plausible local climate scenarios in Canadian Arctic coastal zones.

Assessment and characterization of extremes

- Trend analysis showed that recorded series displayed significant positive trends in annual mean daily minimum temperature over most part of Canada and in annual mean precipitation over SE Canada. However, this trend was not well captured by climate models especially for precipitation. Important differences in detected trends between station records and NRCan gridded datasets were also observed.
- Extreme indices for precipitation and temperatures proposed by the Expert Team on Climate Change Detection and Indices (ETCCDI; Klein Tank et al., 2009) were selected (Table 3).

Modeling of wave and fast ice dynamics in Baffin Bay and Hudson Bay

- Preliminary simulations showed that the upgraded WAVEWATCH III model is well-behaved in a realistic configuration and that further steps can be undertaken towards the production of present (Year 2) and future climate simulations (Year 3).

Climate indicators for upcoming IRIS reports and ArcticNet projects

- An outline of the Climate Chapter contents and potential contributing authors for the IRIS-4 Update Report and an initial list of climate indicators were developed in December 2015. The initial list of climate indicators is based on previous IRIS-4 work as well as recommendations to include additional indicators related to climate extremes (objective 2b; see Table 3).
- The list of indicators was sent to the currently identified chapter leads of the IRIS-4 update report for feedback and is being discussed further in the project. Work was also carried to obtain and update the climate datasets needed to characterize the recent climate trends and variability over the IRIS-4 region. The climate chapter will include information on the coastal climate of the IRIS-4 region (wave, wind and fast-ice) discussed in objective 3a.
- Our involvement in ArcticNet has led to collaboration with the research team of Prof. Gilles Gauthier (Department of biology at Université Laval & Center for Northern Studies). An ensemble of 10 climate scenarios for daily mean temperature has been provided in January 2016 for a research project on the anticipated response of Arctic-nesting goose populations to future climate change. The ArcticNet project "Effects of climate shifts on the Canadian Arctic wildlife: Ecosystem-based monitoring and modeling" (PIs: Dominique Berteaux and Gilles Gauthier) will benefit from these scenarios.

DISCUSSION

Univariate wind speed post-processing

Scenario construction for surface wind speed and direction, both univariate and multivariate (with temperature) will be the major focus of Year 2. This research will build on post-processing principles explored for the temperature-precipitation case as well as on Year 1 results for the wind products.

Consideration of observational uncertainty (OU) in post-processing

Preliminary comparison of indices in historical climate estimated from available datasets has showed that differences depend on the index used. Identifying a unique reference dataset to characterize the historical climate over the whole Arctic is therefore difficult. One approach being evaluated for this problem is to use a multi-dataset reference in the post-treatment process.

Assessment of multivariate post-processing methods

The part of this objective that concerns the multivariate combination temperature-precipitation has been completed, with the publication of the paper by Gennaretti et al. (2015). Scenarios for Arctic-related projects (and others) can now be produced following methods that take into account several principles explored by Gennaretti et al. (2015), namely the preservation of model trends and variable interdependence structure during post-processing. For example, the scenarios provided in January 2016 to the partner project "Effects of climate shifts on the Canadian Arctic wildlife: Ecosystem-based monitoring and modeling" (PIs : Dominique Berteaux and Gilles Gauthier) benefited from scripts developed for model trend preservation. The multivariate structure of air temperature and winds will be explored in Year 2.

Assessment and characterization of extremes

Mean index values over the Arctic estimated from climate simulations and reanalysis daily precipitation series were similar and close to corresponding values estimated from stations series for RX1day, RX5day and No_p99 and slightly higher for PR1mm and No_p95. Values estimated from the NRCan gridded dataset were generally slightly higher than corresponding station values for indices related to precipitation intensity (PRmean, RX1day and RX5day) but were similar for indices related to the frequency of occurrence (PR1mm, No_p95, No_p99). The comparison between climate models also showed that Canadian models outperformed the other models over the Arctic. Comparison of climate mean indices and 99th and 95th percentiles of daily precipitation over the reference period for the Arctic stations and the corresponding closest grid points revealed that, for some indices, models and reanalyses outperformed the NRCan gridded dataset. This last result is important and demonstrated that, as expected, interpolated precipitation datasets should be used with caution in regions with low station density.

Modeling of wave and fast ice dynamics in Baffin Bay and Hudson Bay

Waves-in-ice models so far developed have been implemented and tested in a rather simple one-dimensional framework, in which wave energy losses arising from the scattering response of a collection of ice floes are considered as attenuation. The two-dimensional numerical framework of WW3 allows representing wave energy losses as a scattering and dissipation part. This separation, although more physically coherent and complete, impose that additional tests and verifications be made to insure that the overall wave spectrum is realistic. The preliminary tests realized over short simulations both in idealized and in realistic conditions of Hudson Bay have help identify and solve technical implementation problems. This effort is carried in close collaboration with a team of researchers at Ifremer who also perform tests in other domains (e.g. the Arctic Basin), thus increasing the confidence in the model. In parallel, development is done with respect to wave-induced break-up, which, when coupled to realistic simulated waves-in-ice conditions, will help determine more precisely the risk of having landfast ice destroyed by waves. However, there is observational datasets against which the model could be tested and validated. Wave climate evaluations promised as part of this project will need to be considered as the best guess possible integrating our best understanding of processes at play.

Climate indicators for upcoming IRIS reports and ArcticNet projects

Efforts are being made to ensure that the climate indicators included in the IRIS-4 update address the needs of the report contributors and the local communities in the region. However, the indicators must be physically meaningful and based on a sound methodology. Further refinement of indicator selection and development by the project team is taking place over last quarter 2015/16.

CONCLUSION

The first year of the project was mainly devoted to the gathering of datasets, definition of reference periods (historical and future periods), identification of relevant climate indices, and preliminary statistical analysis. One exception has been the upstream objective related to multivariate post-processing where rapid progress in our thinking contributed to an early publication. These results have already influenced the way climate scenarios are constructed for ArcticNet partner projects.

CORDEX simulations for the North America domain will be analyzed during the next year. Some indices related to rainfall occurring during winter will also be integrated since it has been identified as an important climate indicator for upcoming IRIS reports and some ArcticNet projects.

Characterization of winds in historical climate as well as the development of projections related to winds has become in the recent months a very important issue. There is growing interest in the characterization of winds in historical climate as well as the development of wind-related climate projections for a wide range of applications. In response to these needs, Ouranos organized a workshop in Montreal on November 18, 2015, entitled “Wind and climate change”. The workshop was attended by ~60 people with diverse interests covering areas such as meteorological observation, forecasting and climate projections. The main objectives were to identify Canadian experts in the domain and key data sources, and to assess whether existing wind-related climate information was adequate to meet user needs. The output from the workshop is helping guide Ouranos in the development of climate scenarios and provision of wind-related climate information for ArcticNet.

Results indicate that multivariable post-processing methods can be used to simultaneously post-process variables and preserve the correlation structure between these variables (for instance temperature and precipitation). Such post-treatment methods are important for the development of projections for indices combining two climate variables. Multivariable post-processing methods will be applied to the estimation of relevant indices using available datasets during the next year of the project.

Use of station records as reference datasets for extreme indices, especially those related to precipitation, was considered despite a sparse coverage in the Arctic. Results showed that station records provide valuable and important information for the post-treatment of reanalysis and climate models. Investigations are planned on how station records could be used as a reference dataset for the post-treatment of climate simulations for precipitation and temperature extremes from available climate simulations.

Contacts with report contributors and the local communities in the region have identified a number of additional relevant climate indicators that need to be added to the current list. An ongoing dialogue with potential users is being maintained to ensure that indicators and scenarios respond to their needs.

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The Arctic Snowcover: Sensitivity, Change, and Impacts on Terrestrial Systems, Water Resources and Communities

Project Leader

Philip Marsh (Wilfrid Laurier University)

Network Investigators

Jennifer Baltzer (Wilfrid Laurier University)
Aaron Berg (University of Guelph)

Collaborators

Christopher Derksen (Meteorological Service of Canada - Climate Research Branch)
Glen Liston (Colorado State University)
Oliver Sonnentag (Université de Montréal)

HQP

Evan Wilcox, Honours Undergraduate Student (Wilfrid Laurier University)
Katherine Black, Masters Student (Wilfrid Laurier University)
Philip Mann, Masters Student (Wilfrid Laurier University)
Branden Walker, Masters Student (Wilfrid Laurier University)
Cory Wallace, Masters Student (Wilfrid Laurier University)
Elizabeth Wrona, Masters Student (University of Guelph)
Dawn Keim, Post-Doctoral Fellow (University of Saskatchewan)
Ally Toure, Post-Doctoral Fellow (Wilfrid Laurier University)
Tyler de Jong, Research Associate (University of Ottawa)
Thomas Giguere, Undergraduate Student (Wilfrid Laurier University)

ABSTRACT

Snow is a keystone characteristic of the Arctic, with important controls on, and interactions with permafrost, lake and river ice cover; wetland and stream hydrology; vegetation, wildlife habitat including caribou, fish and waterfowl. Rapidly changing climate is resulting in dramatic transformations to the arctic snowcover. The best documented change is the shortening of the snow season. Although in many regions the snow season is ending earlier in the spring, in others it's starting earlier in the fall, and in some cases resulting in a longer snow season. In addition to changes in snow season duration, other changes in snow depth are also likely to be changing across the circumpolar Arctic. Local scale changes that directly impact human communities, infrastructure and wildlife such as caribou, fish and waterfowl have not been well described. There is an urgent need to address this limitation. Critical knowledge gaps are obvious and there is an urgent need to better understand changes in snow and the impacts on communities, infrastructure, and to steer public policy and the development of natural resources.

KEY MESSAGES

- Snow cover plays a key role in many aspects of the arctic terrestrial environment and it is changing rapidly in response to a warming climate. Snow is also changing in response to related changes in shrub cover and winter precipitation with precipitation increasing in some areas, but decreasing in others.
- Understanding the impacts of a changing snow cover is required to understand many aspects of the terrestrial arctic, including permafrost, streamflow, lake levels and vegetation for example.
- However, these cannot be studied in isolation. Instead there is a need to consider the integrated effects of a changing climate on the snow cover, soil moisture, permafrost and shrubs.
- This project is focused on understanding these complex interactions and through a well-designed program that combines multi-disciplinary focused field observations, remote sensing and high resolution modelling.
- The 2015 spring and summer period was extremely unusual, with the lowest end of winter snow cover since 1991 and one of the earliest and most rapid melt periods on record. One impact of this early and rapid melt period was a long snow-free period, with unusually deep active layer thaw.
- We have made a key advance in calibrating Cosmic Ray Soil Moisture systems that provide soil moisture over a large area. This is a key step in our characterization of the tundra environment and will provide important data for model and remote sensing validation.
- We have demonstrated the utility of an Unmanned Aerial System (UAS) to mapping snow cover depth, snow covered area, and vegetation. This greatly expands our ability to document the landscape.
- A shrub classification map is being completed and we are making excellent progress in quantifying the links to the abiotic landscape and understanding shrub sap flow and evapotranspiration.
- Eddy covariance observations of water, energy, and carbon fluxes is ongoing. This is one of the few such measurements in Arctic Canada and provides key information to understanding the links between vegetation and hydrology. This will also provide a key model validation data set.
- Both large scale (CLASS) and small scale (SnowModel and GEOtop) models have been installed and initial testing is ongoing. These models will allow us to carry out numerical experiments to better understand the links

between climate, permafrost, snow, and vegetation, and the controls on streamflow and lake level.

OBJECTIVES

We are on track and continue to pursue our original objectives to:

1. Determine past changes in climate, shrubs and snow cover for tundra regions of the Western Canadian Arctic;
2. Document the associations between weather, shrubs, active layer moisture/temperature on snow cover formation and melt;
3. Characterize the interactions and feedbacks between snow and shrubs; and
4. Conduct modelling experiments with improved snow models to document the contrasting roles of climate, shrubs, and BC on snow cover over the past decades and under future climate scenarios.

INTRODUCTION

Snow is a keystone characteristics of the Arctic, with important controls on, and interactions with, active layer temperature and thickness; permafrost processes such as ice wedge cracking and rapid lake drainage; lake and river ice cover; wetland, lake and stream hydrology; terrestrial ecology and biogeochemistry including vegetation, wildlife habitat and carbon and energy cycle processes; and aquatic ecology including key fisheries. A rapidly changing climate is resulting in dramatic transformations to the arctic snow cover (Vaughan et al., 2013). Although changes in arctic snow cover have been documented at large scales (Derksen and Brown, 2013), local scale changes that directly impact human communities, infrastructure and wildlife such as caribou, fish and waterfowl, have not been as well described. There is an urgent need to address this limitation. Critical knowledge gaps are obvious at both the large and small scale, and are indicated by poor modelling results. For example, satellite observations of spring snow cover show much earlier snow free conditions when compared to multi-model ensemble consensus (Derksen and Brown, 2013). Shi et al. (2015) documented earlier start of spring snowmelt, but later spring melt runoff in the western Canadian Arctic. The reasons for both of these are not well understood, but the direct effects of increasingly warming temperatures and altered precipitation are likely not sufficient to explain the observed changes in the snow and streamflow regimes. Contributing factors might include increasing area of tundra covered by shrubs for example as this can result in conflicting changes, including decreased albedo and hence increasing melt, reduced wind speed and decreased melt, and trapping of more blowing snow resulting in deeper snow cover (Liston and Hiemstra, 2011; Liston et al., 2007) and delayed melt in shrub patches. Although in some cases shrubs result in a longer snow-covered season (Menard et al., 2012), the actual effect of shrubs on snow cover is dependent on shrub properties, shrub patch size and the location of the patches on the landscape. Shrubs also have direct impacts on the spatial and temporal patterns in energy fluxes (Endrizzi and Marsh, 2010) and therefore active layer temperature and thickness (Blok et al., 2010), moisture, watershed runoff, and terrestrial ecology. Existing models are unable to explain this delayed spring melt runoff (Shi et al., 2015) that has been described in the Western Arctic in spite of increasing spring air temperature, decreasing snowfall, and earlier start of snowmelt. There are key knowledge gaps related to factors controlling shrub patch location (in stream valleys or at the base of slopes below snow drifts for example) and expansion, and the impact of this on snow cover through controls on blowing snow transport and deposition. Unravelling these competing effects and interactions of changes in climate, shrub expansion, remains an important challenge acknowledged by the IPCC, the Canadian Polar Commission and Polar Knowledge Canada. Improved understanding of the integrated arctic system will lead to the improved predictive tools that are required for improved future climate projections, and to consider the implications of a changing arctic climate on key aspects of the arctic environment (snow, permafrost, hydrology, ecology), built environment (cities, towns, industry, and supporting infrastructure), and social systems. Changes in snow will have many impacts on northern aboriginal communities that rely on over snow transport for recreation and hunting, and depend on country foods that rely on snow, including fish, caribou, and waterfowl. Given the importance of snow in the regional climate system and to hydrology, snow models play an important role in climate modelling, and land surface models must include snow in order to consider the effect of the snow-albedo feedback. To address these research needs, the overall goal of this project is to develop an improved understanding of past changes in snow cover and spatial and temporal variations in current snow, shrubs and active layer. Building on these, we will develop an improved ability to predict future changes in arctic snow cover in response to the integrated impact of several environmental

ACTIVITIES

Time frame and study area: Field work, with researchers on site, was carried out from April to September 2015, and one day in November for sensor removal and data downloads, at the Trail Valley Creek (TVC) Research Watershed located 50 km north of Inuvik and 75 km south of Tuktoyaktuk. During the April to September period we carried out observations across the TVC watershed (58 km^2), and also focused more measurements in the Siksik Creek sub-watershed (1 km^2). In addition, many of our instruments recorded key data during the winters of 2014-15 and 2015-16. These include: multiple weather stations; time lapse cameras; a soil moisture and snow water equivalent network using cosmic ray sensors; eddy covariance systems; soil temperature and shrub tilting network; and other sensors and loggers. However, as these systems were unattended over the winter periods, there were occasional data collection problems with snow and ice limiting the accuracy of the data and a few cases of battery or instrumentation failure. Although not directly part of our ArcticNet project, we have been carrying out complementary measurements at a forested watershed close to the Inuvik Airport in order to have comparisons to a fully forested basin that may be similar to our main study site in the future (Figure 1).

Camp Infrastructure: Our science activities were directly supported by the further development of the camp infrastructure at the main Trail Valley Creek camp through CFI and other fundiing. These updates were required to increase camp sleeping and work space, improve AC electrical power supply to ensure use of numerous computer systems, complex data loggers, and data archiving abilities, and to improve cooking and hygiene capacity. This was required in order to house scientists from our ArcticNet project as well as other related projects and international collaborators.

Research: Intensive field work focused on end of winter snow cover, snowmelt and changes in snow covered area over the melt period; summer soil moisture and active layer thickness; eddy covariance measurements; and detailed vegetation measurements.

Automatic Weather, soil and snow stations (AWS^3):

- Data was retrieved from four AWS^{3}s, over tundra, short shrub-tundra, tall alder shrub and white spruce forest land covers. Measurements included: air temperature and relative humidity; wind speed and direction; snow depth; soil temperature; incoming/outgoing short and long wave radiation; and soil moisture.
- Alter shielded Geonor precipitation gauges were located in the lower reaches of the basin and in a nearby sheltered forest clearing. A digital snow pillow was co-located in the forest clearing.

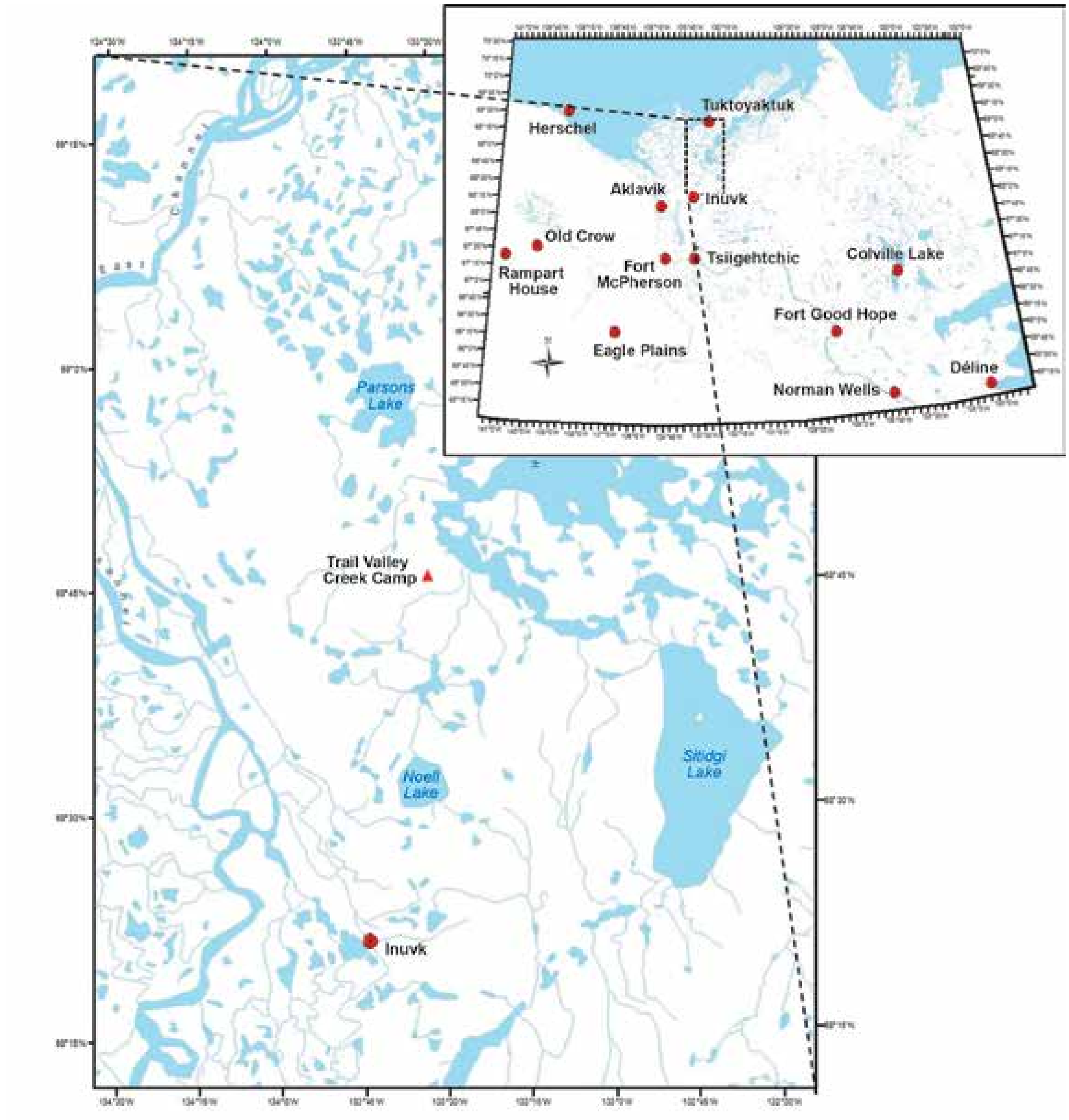

Figure 1. Trail Valley Creek research watershed, showing location in the western Canadian Arctic.

- Three cosmic ray sensors, CRS-1000's, were located at short shrub, forest and tundra sites to measure snow water equivalent and soil moisture.
- The Environment Canada, Meteorological Service of Canada AWS[3], co-located with one of our AWS[3], operated throughout the study period.

Streamflow:

- Environment Canada, Water Survey of Canada, operated their streamflow station at Trail Valley Creek throughout the spring, summer, fall of 2015. These data will be available in the spring of 2016.
- In September 2015, we installed a weir for streamflow observations from Siksik Creek. This

will allow streamflow observations during the spring, summer, and fall of 2016 and 2017.

Snow:

- Snow surveys were carried out in April, prior to the start of melt, by T. de Jong, B. Walker and P. Mann at sites across TVC. These sites have been measured annually since 1991 allowing a comparison of spring 2015 snow to the 1991-2015 record.
- Snow surveys were also carried out within Siksik Creek prior to melt, and during the melt period, by the same team as noted above in order to document end of winter snow cover in much greater detail, and to document the changes in snow cover extent during melt.
- An eBee Unmanned Aerial System (UAS) was flown extensively by T. de Jong to image snow cover at the end of the melt period and during the melt period. Four imaging options were available, RGB, Near-infrared, Multispectral, and Thermal Infrared imagers (only one can be flown at a time). Using the RGB imager, we were able to obtain high resolution images (a few cm in horizontal resolution) for all of Siksik Creek watershed throughout melt. Unfortunately, a software/firmware update at the end of melt (needed to fly the thermal imager) resulted in catastrophic communication failure of the UAS while it was on the ground, and we had to return it to Switzerland for electrical repairs. As a result, we could not fly the UAS again until late August, when we flew the UAS to map vegetation patterns and Normalized Difference Vegetation Difference (NDVI) and to obtain a snow free digital elevation model.
- In addition to the CRS-1000 noted above, a string of eight cosmic fay SnowFoxes were installed across a shrub patch in order to changes in snow water equivalent (SWE).

Soil Moisture:

- Active layer soil moisture variation was measured at various scales and focused on several different approaches. The CRS-1000 cosmic ray instruments offer many advantages as they integrate soil moisture over a relatively large sampling region (approximately 100,000 m^2). This large integration region is advantageous for both hydrological and remote sensing studies. Traditional point based methods are limited to sampling regions of 10 s of cm^3 and therefore subject to the very high spatial variability of soil moisture observed in this region. In addition to the CRS-1000's we used both an extensive network of soil moisture sensors within the footprint of the cosmic ray sensors, and soil moisture observations along several transects where hundreds of soil moisture observations were obtained. Along with the soil moisture observations measurements of shrub presence and frost table depth were also taken.
- A model was derived for estimating the spatial variability of soil moisture using RADARSAT-2 data and ground observations.

Active Layer thickness:

- Post-doctoral Fellow D. Keim and undergraduate student Evan Wilcox conducted extensive weekly surveys of frost table depth were under taken along transects within Siksik Creek covering a range of tundra, shrubs, creek beds, and late laying snowpack environments. In addition, soil samples were obtained for soil moisture determination. A key component of this survey was to measure frost table in both hummocks and the high hydraulic conductivity inter-hummock areas.

Modelling

- MSc. student William Woodley applied the Canadian Land Surface scheme (CLASS) to simulate active layer depth and soil moisture variation across the study domain.

- Post-doctoral fellow, Dr. Ally Toure, who arrived at Laurier on January 4, 2016, installed SnowModel, a snow modelling system which is composed of four components (a meteorological distribution model, a surface energy balance model, a snow properties model, and a blowing snow model) and GEOtop a high resolution hydrological model. SnowModel complements the snow components in GEOtop, and will provide necessary snow inputs into GEOtop. These models have been installed on the Compute Canada high performance computer. In addition, Dr. Toure has developed the necessary series of driving data for both the winter of 2012/13 (the SnowSAR study winter at Trail Valley) and the 2015/16 ArcticNet study year.

Shrub vegetation:

- *Alnus viridis* (green alder) has unique potential to drive change relative to other shrub species growing in tundra systems north of Inuvik, NT. This work aims to understand the constraints for and consequences of alder shrub growth in this low-arctic system.
- This work provides a unique dataset regarding the constraints on alder expansion at two spatial scales, furthering our understanding of shrub patch dynamics and expansion and providing useful information for climate change and hydrological modeling in the North.
- To determine constraints on the distribution of green alder at the landscape scale a land cover classification was developed by C. Wallace and others to identify shrub patches (discrete shrub communities) on the landscape. These locations will be compared to remotely-sensed imagery of snow distribution, aspect, and soil moisture providing important information regarding constraints of landscape-scale shrub distribution. This will allow us to characterize differences between shrub patches and the surrounding tundra environment, of which little is currently known.
- Transects were run through 10 alder patches and 10 open tundra locations adjacent to the patches. These patches were established along topographic gradients and paired open tundra measurement sites were established at each topographic position (Figure 2). Several biotic and abiotic measurements were made along these transects including plant community composition and structure, maximum thaw depth, soil moisture, organic layer depth, and canopy cover.
- To explore constraints on alder regeneration at the patch scale two experiments were carried out. First, alder seedling densities were determined across the topographic gradients depicted in Figure 2 using plotless sampling methods as well as quadrat counts. Second, experimental manipulations of abiotic conditions as well as seed availability will be employed in 2017 in order to expand this objective.

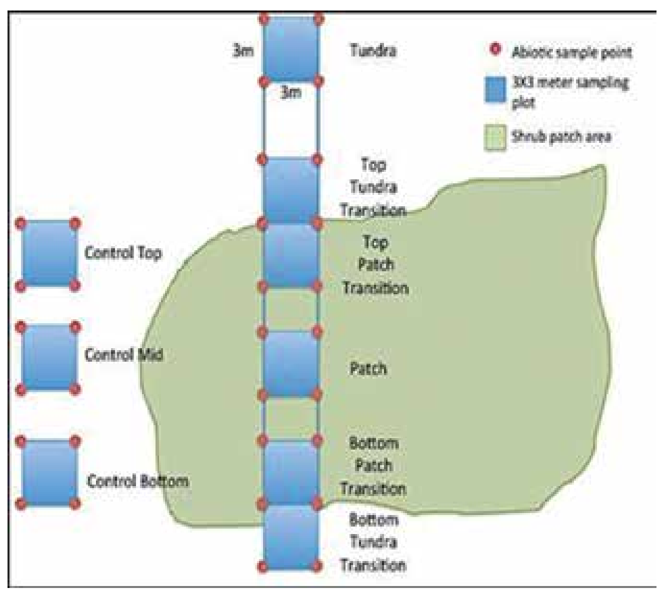

Figure 2. 2015 sampling design. Transects were established downslope through 10 patches on south facing slopes and adjacent open tundra locations. 3x3 m quadrats were placed along these transects, specifically targeting the transition zones from the tundra to patch conditions. Maximum thaw depth, soil moisture, and organic matter thickness were measured at the corners of all 3x3 m quadrats.

- 32 alder individuals were instrumented with heat ratio method sap flow sensors. At eight of the ten patches described above, we instrumented individuals at each of four positions: plateau, mid-slope, slope bottom and drainage channel. We have continuous sap flow data from early June to late August capturing the majority of the growing season. We are currently measuring sapwood area on cookies from these shrub stems in order to facilitate upscaling of shrub water use to larger areas. Shrub water potential measurements were made across these same gradients in order to assess whether shrubs experience drought stress on any part of the landscape during the growing season. Finally, leaves from all of these shrubs were collected for nitrogen analysis to assess whether landscape position and water availability impacted plant nutrient availability. These data will all be analysed before the 2016 field season thereby guiding refinement questions surrounding water and nutrient constraints on shrub distribution.

Eddy covariance:

- In April 2013 we initiated eddy covariance measurements at the Trail Valley Creek watershed to continuously monitor net carbon and water and energy exchanges between the land surface and the atmosphere.
- These measurements complement a series of radiometric (e.g., net radiation and its components) and environmental measurements (e.g., soil moisture and temperature) that started in 1991. Understanding these fluxes is a key component of understanding snow melt, soil moisture and ecological conditions across this rapidly evolving tundra landscape.
- Despite some technical difficulties resulting in instrument malfunctioning and thus data loss (e.g., latent heat), we continued with this comprehensive set of measurements throughout 2015.

Snow Remote Sensing:

- Soil and snow measurements from TVC contributed to the validation of the landscape freeze/thaw product derived from L-band radar measurements from the NASA Soil Moisture Active Passive (SMAP) mission.
- The beta release of the SMAP dataset occurred in October 2015, with the final validated release schedule for April 2016. Following the failure of the SMAP.
- Trail Valley Creek is a core validation site for the NASA SMAP freeze/thaw product, providing a unique suite of soil and snow measurements in a shrub tundra environment.
- Radar in July 2015 for TVC were used to assess the capability to shift the freeze/thaw product to SMAP radiometer (passive) measurements.
- Trail Valley Creek represents an important site for ongoing analysis of radar interactions with terrestrial snow. Ongoing radar retrieval development (using experimental airborne data acquired in 2012/13) and recently initiated distributed hydrological simulations are core components of mission concept studies for new snow radar systems, underway at CSA and ESA.

RESULTS

The 2015 field season was extremely productive, and analysis of the data is proceeding. All of our studies are on schedule. Key new findings and advances are outline below:

Weather Conditions:

- Analysis of the 2015 data is ongoing in order to put this year into the long term context in terms of temperature and precipitation. Early analysis shows that the 2015 melt period was the earliest on record (since 1958), and likely had the highest temperature (20^{o}C) during the melt period. The implications of this to the hydrological year are being analyzed.

Snow:

- End of winter Snow Water Equivalent was the lowest on record. This, when combined with an extremely early and rapid melt, resulted in an extremely unusual spring melt season, and one of the longest snow free summers on record. Full analysis of these data is waiting Water Survey of Canada to release the 2015 streamflow data.
- Preliminary results demonstrate that the UAS images, when analyzed using structure-from-motion software, are able to map the elevation of the snow surface and allow the mapping of snow depth from subtraction from a LiDAR snowfree data set. This mapping is available at extremely high horizontal resolution. Preliminary results suggest that errors in vertical snow depth are less than 25 cm, allowing for the first time snow depths to be mapped at fine resolution across a watershed. This has enormous implications for our understanding of snow distribution, and for providing the necessary data sets for testing snow models. Preliminary data suggest that earlier methods based on snow depth probing, greatly under estimate the range of snow depths across a watershed and show many more deep snow drifts than were observed by simple snow depth sampling.
- However, the UAS snow depth mapping results point to a limitation of our knowledge. Namely, the spatial variability in snow density. In order to use the UAS derived snow depths for hydrological purposes, we also need to estimate snow density at this scale. We will devise an appropriate field study for the spring of 2016 to address this issue. See Figure 3 and Figure 4.

Soil Moisture:

- Graduate student Elizabeth Wrona developed a calibration equation to relate measured cosmic ray flux to soil moisture. These results were presented at the ArcticNet annual meeting. This work has clearly shown that this method works well, and will help address a major limitation in arctic monitoring – very poor soil moisture measurements. This is another major advance.
- A former MSc. student Rachel Humphries (MSc. 2015) further evaluated controls on the variability of soil moisture within the cosmic ray sampling region. This study indicates a strong relationships between soil moisture and the presence of shrubs and variation of the microtopography. A manuscript based on these results was submitted.

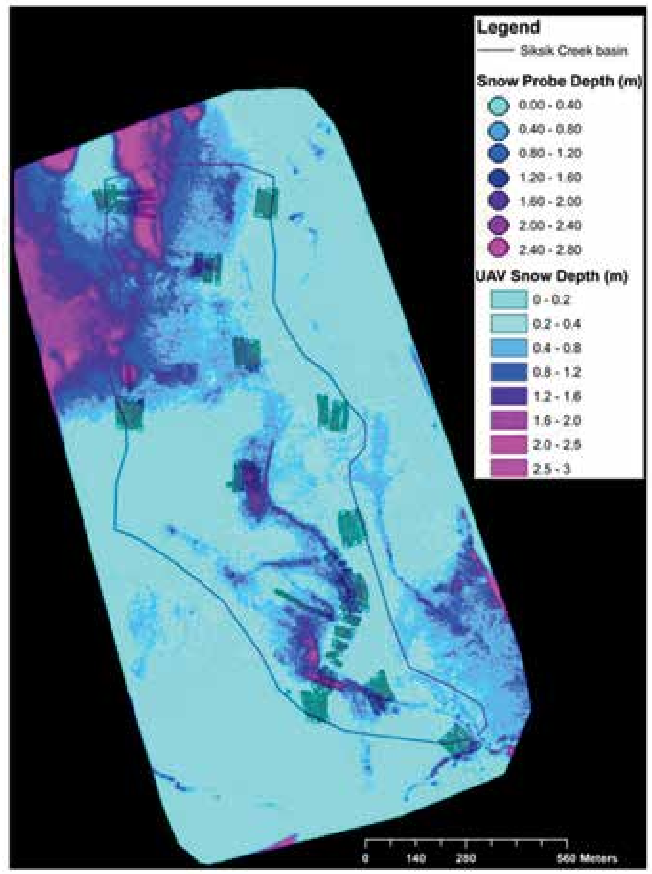

Figure 3. Map of end of winter snow depth derived from the UAS images.

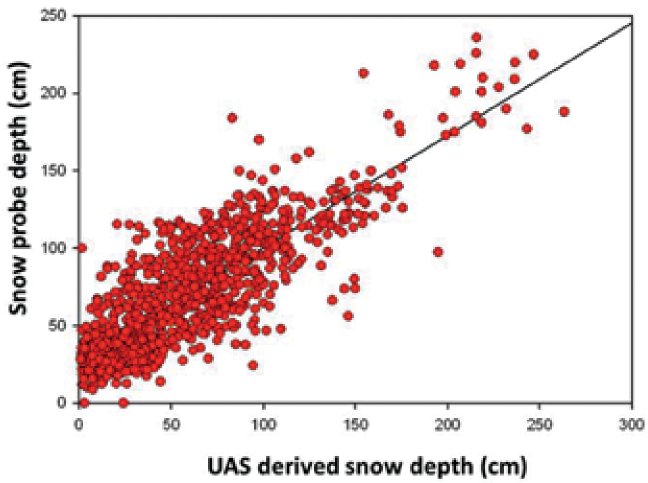

Figure 4. Relationship between UAS snow depth and manual measurements of snow depth.

Active Layer thickness:

- Extensive active layer surveys are being analyzed to quantify the spatial and temporal variability in frost depth and will provide important information on the development of water pathways controlling streamflow response. In addition, they will help with understanding the relationship between shrubs, topography, and active layer – a topic of considerable uncertainty and importance. Finally, these data will be a key data set for GEOtop validation. Preliminary analysis of these data show that end of summer active layer depths are much deeper than when similar surveys were completed in the mid-1990's. Analysis, and modelling, are ongoing to better understand these changes.

Shrub vegetation:

- The shrub classification is nearing completion, but requires comparison to collected "ground truth" data from existing high resolution aerial photographs from which alder distribution for small areas is very clear. This classification will be completed before the start of the 2016 field season.
- The large plant community composition dataset is currently at the data entry stage but preliminary results on abiotic conditions are presented below.
- We have made good progress in understanding changes in the abiotic environment. As evidenced in Figure 5, tundra and shrub patch sites clearly differentiate based on abiotic conditions particularly with respect to active layer thaw processes and organic layer thickness. Key differences between tundra and shrub patches include a thinning of the active layer within shrub patches (Figure 6), which may be attributable either to shading by the shrub canopy, extended snow melt period and therefore shortened snowfree period, or reductions in soil moisture below shrubs (Figure 7) caused by greater evapotranspirative demand by shrub canopies (data analysis in progress). Ongoing studies will use GEOtop to consider these processes. We also found consistently deeper organic layers

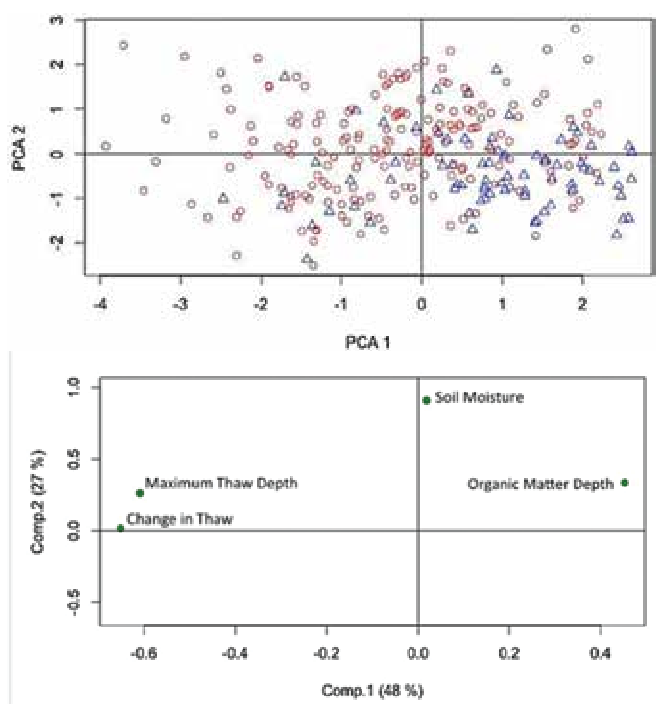

Figure 5. a) Loading values for principal component analysis. b) PCA scores displayed by location. Location in shrub or tundra improved explanation of Component 1 and 2 (p<0.0001).

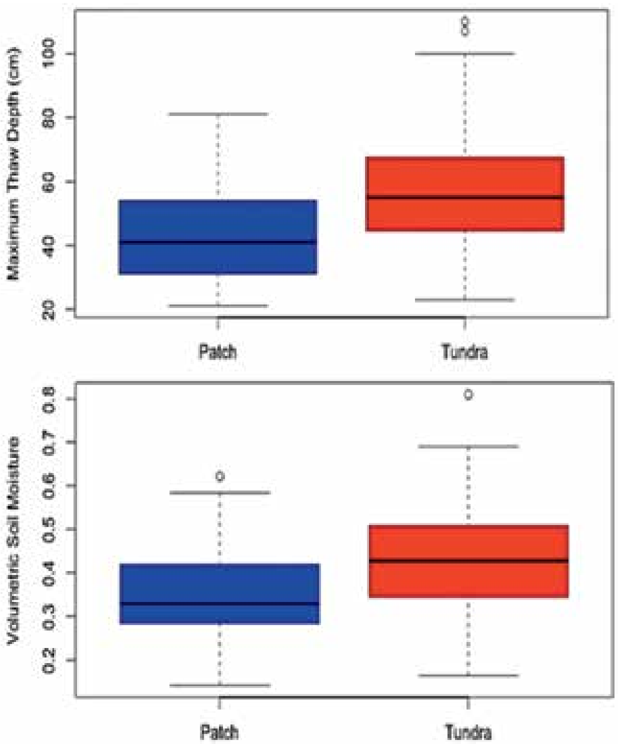

Figure 6. Maximum thaw depth (a) and soil moisture (b) by location. Location improved explanation of both variables, suggesting greater thaw and wetter soils in the open tundra compared to shrub patches (p<0.0001).

within shrub patches (Figure 7), which may be a function of the enhanced litter input by deciduous shrubs but has important implications for physical and biological active layer processes. Preliminary results from alder seedling density surveys indicate very low levels of sexual reproduction around shrub patches regardless of topographic position, potentially implicating vegetative reproduction as a key process (Figure 8). Finally, shrubs are experiencing differential drought stress as a function of topographic position (Figure 9).

- We will gain much insight on the role of vegetative reproduction in the coming summer through experimentation, seed viability analysis and enhanced reproductive surveys.

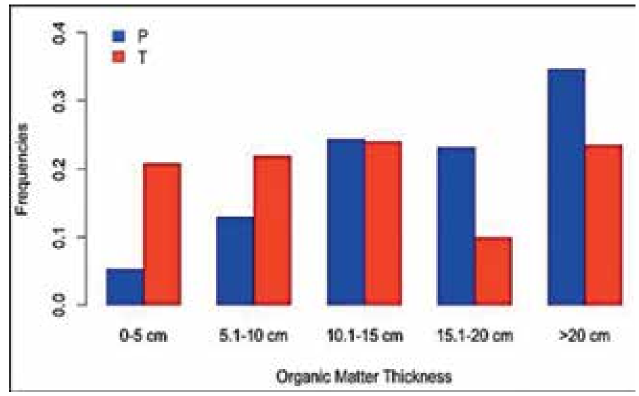

Figure 7. Frequency of organic matter depth categories by location. Frequencies differ significantly from expected (p=0.0004) with patches containing the majority of deeper sites and tundra containing the majority the shallow sites.

Eddy covariance:

- 2015 eddy covariance and supporting measurements are currently being processed and added to the growing data archive. Fanny Payette, a graduate student in the Département de géographie at the Université de Montréal recently submitted her MSc thesis, comparing turbulent fluxes of latent and sensible heat between the Trail Valley Creek watershed north of the treeline and the Havikpak Creek watershed south of treeline. A manuscript on her results is currently being written, potentially including some of the 2015 measurements made at the Trail Valley Creek.

Snow Remote Sensing:

- Time series of descending overpass SMAP L-band radar backscatter and radiometer normalized polarization ratio (NPR) along with coincident soil and air temperature measurements for TVC during spring 2015 are shown n Figure 10. There is clear L-band response (both active and passive) to freeze/thaw transitions, with evidence that the radar and radiometer FT flags are responding to the onset of wet snow, as indicated by transient early season thaw events when air temperatures exceeded zero (hence

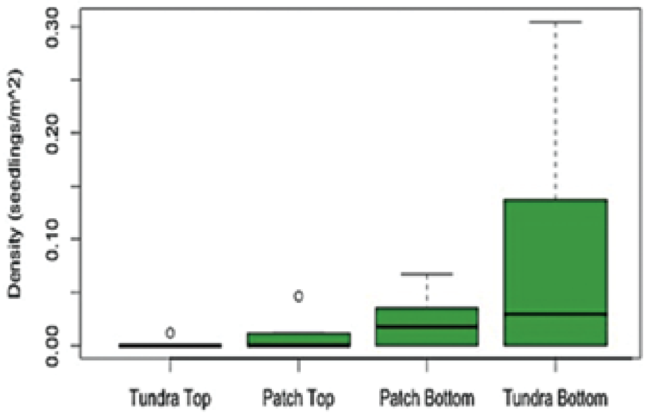

Figure 8. Juvenile seedling density downslope through patches (n.s.).

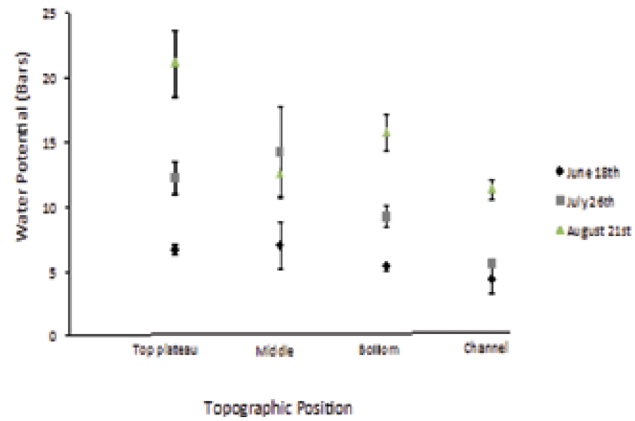

Figure 9. Shrub water potential as a function of topographic position and growing season period. Water potential corresponds predictably with topographic position.

inducing snow melt) but soil temperatures remained below zero. These events are more frequent with the ascending overpasses due to warmer afternoon temperatures (not shown). The ongoing measurements at TVC are making an important contribution to SMAP freeze/thaw validation, which in turn supports the use of SMAP products for ecological and hydrological applications across Canada (Figure 10).

Modelling

- CLASS model results suggest that the simulation of the active depth and soil moisture variation can be represented more accurately if the model is changed to allow significantly more soil layers (10) than is typically used in global simulations (3). Further, it was found that unless slopes are simulated in the CLASS framework, the low evapotranspiration rates and low rates of deep drainage result in unrealistic saturation within the model. These results were presented at the ArcticNet annual meeting.
- Initial SnowModel and GEOtop model runs are ongoing. These model runs will be completed prior to the 2016 field season and will be used to guide, and fine tune, the upcoming field observations.

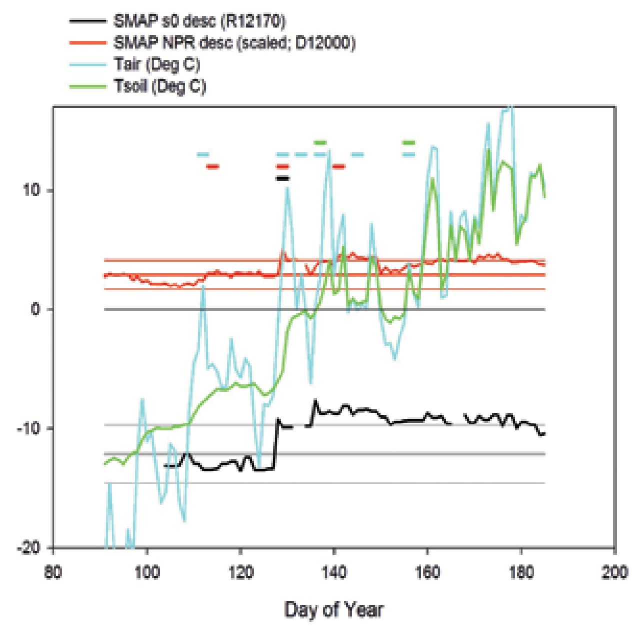

Figure 10. Time series of SMAP backscatter, normalized polarization ratio, air temperature, and soil temperature (left) and flag agreement (right; blue = freeze, red = thaw) for Trail Valley Creek during the overlap period of SMAP radar and radiometer measurements. Horizontal dashed lines note freeze/thaw transition periods.

DISCUSSION

Our first field season was extremely successful, and preliminary data analysis and modelling is showing that we are on track to answer the key questions raised by this project. This is namely, can we improve our understanding of the interaction between key aspects of the terrestrial environment, namely the complex interactions between climate, snow, active layer, soil moisture, shrubs, and streamflow. Understanding these complex interactions, and testing, improving and validating predictive models are key to understanding past changes to this system, and considering future changes as the climate continues to dry, and the precipitation changes (precipitation has decreased over the last 60 years in this region, but is forecast to increase in the coming decades.

CONCLUSION

During our first 10 months of this ArcticNet project, we have made tremendous progress, and are on track to meet all of our objectives. Our field work, with staff and students on site at Trail Valley Creek (a total of approximately 500 person days), was extremely successful. We have verified the utility of a number of new instruments, including Cosmic Ray Sensors and an Unmanned Aerial System. These have greatly enhanced our ability to measure snow cover and soil moisture. We have also made significant advances in mapping shrubs and in measuring sap flow. Although we had significant instrument issues with our eddy covariance system in the summer of 2015, these have been repaired and the system is working and we are expanding our multiple year data set. Metadata on key aspects of our data collection have been input to the Polar Data Catalogue, and we are continuing to add additional metadata. Finally, we were delayed in hiring a Post-Doctoral Fellow, but Dr. Ally Toure joined our team in January 2016. We were extremely fortunate to attract Dr. Toure from the NASA Goddard Space Flight Centre where he was doing regional scale modelling. Dr. Toure brings a range of modelling skills to our project, and will be instrumental in linking the various aspects of our project together, and to do high resolution modelling experiments to help understand how this system has changed in the past decades, and how it will change in the future.

ACKNOWLEDGEMENTS

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Coupled Terrestrial-Aquatic Climate Impacts on High Arctic Watersheds: Using the Lake Hazen Watershed as a Sentinel for Change

Project Leader

Vincent St.Louis (University of Alberta)

Network Investigators

Michael English (Wilfrid Laurier University)
Igor Lehnherr (University of Alberta)
Derek Muir (University of Guelph)
Alexandre Poulain (University of Ottawa)
Sherry Schiff (University of Waterloo)
Martin Sharp (University of Alberta)
John Smol (Queen's University)

HQP

Pieter Aukes, Doctoral Student (University of Waterloo)
Paul Dainard, Doctoral Student (University of Waterloo)
Ashley Dubnick, Doctoral Student (University of Alberta)
Colleen Mortimer, Doctoral Student (University of Alberta)
Matti Ruuskanen, Doctoral Student (University of Ottawa)
Kyra St-Pierre, Doctoral Student (University of Alberta)
Bradley Danielson, Post-Doctoral Fellow (University of Alberta)
Craig Emmerton, Research Associate (University of Alberta)
Neal Michelutti, Research Associate (Queen's University)
Maya Abou-Ghanem, Technical Staff (University of Alberta)
Yuting (Tina) Chen, Technical Staff (University of Alberta)
Thomas Cornell, Technical Staff (University of Waterloo)
Crystal Dodge, Technical Staff (University of Alberta)
Richard Elgood, Technical Staff (University of Waterloo)
Jennifer Hickman, Technical Staff (University of Waterloo)
Yue (Ruby) Jiang, Technical Staff (University of Alberta)
Wendong (Neil) Liu, Technical Staff (University of Alberta)
Alex MacLean, Technical Staff (Wilfrid Laurier University)
Philip Pelletier, Technical Staff (University of Ottawa)
Kelita Pratt, Technical Staff (University of Waterloo)
Charles Talbot, Technical Staff (Environment Canada - Canada Centre for Inland Waters)
Janessa Zheng, Technical Staff (University of Waterloo)
Stephen Langmaid, Undergraduate Student (University of Alberta)
Ryan Walters, Undergraduate Student (University of Alberta)
Haihan Wang, Undergraduate Student (University of Alberta)
Catherine Wong, Undergraduate Student (University of Toronto)
Debbie Zheng, Undergraduate Student (University of Waterloo)

Northern HQP

Steven Akeeagok, Northern Student (Parks Canada - Nunavut Field Unit)

ABSTRACT

A whole-ecosystem study is being conducted to quantify coupled terrestrial-aquatic impacts of climate change on high Arctic watersheds, using the Lake Hazen watershed in Quttinirpaaq National Park on northern Ellesmere Island, Nunavut, as a sentinel system. To accomplish this goal, the following are being quantified: 1) net exchange of energy, H_2O, CO_2 and CH_4 between the atmosphere and terrestrial landscapes in the watershed; 2) net mass change of glaciers in the watershed; 3) chemical inputs to Lake Hazen from snowmelt, glacier melt and soil/permafrost thaw; 4) the metabolism of Lake Hazen itself; and 5) long-term biological and biogeochemical changes in Lake Hazen and its watershed using sediment cores. Emphasis is being placed on understanding: 1) sources, quality and age of the organic carbon (OC) and nutrients entering Lake Hazen; 2) 'hot spots' where major biogeochemical processes altering OC and nutrients occur; and 3) the rates at which these biogeochemical processes are evolving. Identification of sources, and quantification of inputs, of legacy contaminants (e.g., mercury, persistent organic pollutants) is being undertaken through a partnership with Aboriginal Affairs and Northern Development Canada and their Northern Contaminants Program. From an applied and socio-economic perspective, increasing our ability to predict impacts of warming northern ecosystems on watershed productivity and water quality is vital for securing food, clean drinking water and traditional lifestyles for Northern peoples.

KEY MESSAGES

- During the growing season, the dry semidesert landscape in the Lake Hazen watershed was a near zero sink of atmospheric CO_2, whereas a nearby wetland in the Skeleton Lake subcatchment accumulated over two magnitudes more CO_2, and was surprisingly similar to wetland productivity at much more southern latitudes.
- Climate change is greatly enhancing glacial melt in the Lake Hazen watershed, where surface temperatures of glaciers have been increasing up to 0.15°C per year since 2000.
- Increased glacial runoff has changed the water residence time of Lake Hazen, resulting in a lag between Lake Hazen water chemistry and chemical inputs to the lake from glacial rivers, and Lake Hazen not being at steady state with respect to its inputs.
- With regards to nutrients, concentrations of NO_2+NO_3 were similar in glacial river inputs to Lake Hazen, throughout the water column of Lake Hazen, and at the Ruggles River outflow of Lake Hazen, whereas concentrations of total phosphorus (TP) were much higher in glacial river inputs than throughout the water column of Lake Hazen, and at the Ruggles River outflow, suggesting that a large portion of the TP entering the lake settles out on particles.
- Concentrations of TP in two frequently sampled glacial rivers (Snowgoose River and Blister Creek) increased with increasing flow intensity, suggesting that erosional materials are the source of the TP.
- With regards to contaminants, concentrations of methylmercury (MeHg) and perfluorinated alkyl substances (PFASs) in the Ruggles River were lower than any of the inflow concentrations, suggesting that a combination of sedimentation, dilution and photodemethylation is occurring in the lake.
- NO_2+NO_3 coming out of a soil/permafrost thaw seep was quickly used up downstream in hydrologically connected Skeleton Lake, ponds and wetlands, suggesting that these types of subcatchments in the Lake Hazen watershed are very N-limited, and rely on efficient recycling of organic nitrogen.
- MeHg concentrations increased as water moved through Skeleton Lake and two downstream ponds, indicating that these were both sites of active microbial mercury methylation.

- Lake Hazen contained low dissolved organic carbon (DOC) concentrations, which may be representative of its primary water source: glacial rivers.
- Small permafrost thaw streams appeared to be localized productive zones, contributing higher concentrations of DOC to surrounding creeks and rivers.
- The increased proportion of biopolymers in DOC from Skeleton Lake suggests a contribution of authochthonous carbon to the DOC pool.
- Results from incubation experiments indicate that photolysis is likely the primary driver for DOC degradation in these high Arctic environments rather than microbial degradation, which has implications for dissolved organic nitrogen and MeHg transport from these environments as they are influenced by the fate of DOC.
- Instantaneous flow measurements taken on the Snowgoose River, Abbé River and Blister Creek proved to be challenging because these glacial rivers are very braided or completely inundated, and flow changes immensely throughout the day and season depending on temperature, but measurements will still be used to ground-truth melt discharge modelling results, as well as the hydrograph from the gauged Ruggles River outflow volume measurements taken by Water Survey Canada.
- Dissolved O_2 concentrations started declining and CO_2 concentrations began increasing below 180 m in Lake Hazen under the ice due to active microbial metabolism in the sediments of Lake Hazen, and no physical mixing of the water column under the ice.
- In late July, both O_2 and CO_2 concentrations were similar throughout the entire 265 m of the water column due to a physical mixing from dense glacial river turbidity currents bringing surface river waters rapidly to the bottom of the lake.
- $\delta^{15}N$ signatures on particulate organic matter (POM) from Lake Hazen suggest that Lake Hazen may be N limited.
- Concentrations of contaminants (MeHg and PFASs) throughout the water column in late July were lower than concentrations measured in May under the ice, and much lower than in river water flowing into Lake Hazen, suggesting that these contaminants are being stripped from the water column on particles that are rapidly settling out to the bottom of the lake.
- Concentrations of CO_2 in shallow waters near the shoreline of Lake Hazen during the summer were always below atmospheric equilibrium not because of CO_2 drawdown from primary productivity, but because of geochemical weathering of carbonate and feldspar minerals added to Lake Hazen in glacial runoff.
- Dissolved O_2 was depleted within the top centimeter of sediments regardless of the depth from which sediments were collected in Lake Hazen, suggesting very active microbial respiration in sediments.
- All of the DNA marker genes tested so far (16S rRNA, *glnA* and *merA*) have been amplified without problems to determine microbial community structure and function in lake sediments.

OBJECTIVES

To examine coupled terrestrial-aquatic impacts of climate change on high Arctic watersheds, our research has five specific objectives. We are quantifying:

1. net exchange of energy, H_2O, CO_2 and CH_4 between the atmosphere and terrestrial landscapes in the Lake Hazen watershed;
2. net mass change of glaciers in the Lake Hazen watershed;

3. chemical inputs to Lake Hazen from snowmelt, glacier melt and soil/permafrost thaw;
4. the metabolism of Lake Hazen itself; and
5. long-term biological and biogeochemical changes in Lake Hazen and its watershed using sediment cores.

Emphasis is being placed on understanding:

1. sources, quality and age of the organic carbon (OC) and associated nutrients entering Lake Hazen;
2. where major biogeochemical processes altering OC and nutrients occur (i.e., hot spots); and
3. the rates at which these biogeochemical processes are evolving.

We are also identifing sources, and quantifing 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).

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 watershed area of 8400 km^2, half of which is glaciated) [11], and supports one of the largest stocks of landlocked Arctic char (*Salvelinus alpinus*), historically harvested by Inuit, Thule and Paleo-Eskimo peoples. 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 nitrate (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 during two intense periods at Lake Hazen in 2015: 1) in the spring when there was still snow on the ground and the lakes were ice-covered (11-22 May); and 2) in the summer during the height of glacial melt and soil/permafrost thaw, as well as ice-off on lakes (25 June to 3 August). During these times in the field, as well as outside the field season, we concentrated on the first four objectives of our research program. However, due to a reduction in funding from what was requested, we shifted focus on some of our activities.

1) Net exchange of energy, H_2O, CO_2 and CH_4 between the atmosphere and terrestrial landscapes in the Lake Hazen watershed:

- No field activities were done for this objective in the summer of 2015 due to transferring funds to Objective 2. Instead we concentrated on publishing our early 2008-2012 datatset on this topic: Emmerton, C.A., V.L. St.Louis, E.R. Humphreys, J.A. Gamon, J.D. Barker and G.Z. Gilberto. 2015. Net ecosystem exchange of CO_2 with rapidly changing high Arctic landscapes. Global Change Biology. doi: 10.1111/gcb.13064 (C. Emmerton, V. St.Louis).

2) Net mass change of glaciers in the Lake Hazen watershed:

- We began working on the design and testing of the GPS units (which consist of survey-grade GPS/GNSS receivers and antennas, and power supply systems designed to keep the instruments operational year-round) to be used to monitor the elastic deformation of the crust driven by changes in glacier mass loading in the Lake Hazen watershed (M. Sharp, B. Danielson).
- We began building the GPS units that will be deployed in the Lake Hazen watershed (M. Sharp, B. Danielson).
- We completed our analysis of the MODIS Land Surface Temperature (LST) record for all glaciers on Ellesmere, Devon and Axel Heiberg islands (M. Sharp, C. Mortimer).

3) Chemical inputs to Lake Hazen from snowmelt, glacier melt and soil/permafrost thaw:

- During our May trip, we quantified winter (October-May) atmospheric loadings of nutrients and other chemical parameters (dissolved N, particulate N, NO_3^-/NO_2^-, NH_4^+, total P, total dissolved P, dissolved inorganic C [DIC], dissolved OC [DOC], total dissolved solids, Cl^-, SO_4^{2-}, major cations/metals) and contaminants by collecting integrated snowpack core samples prior to the onset of snowmelt along a transect in the watershed and on Lake Hazen ice. Snowmelt runoff was not quantified in 2015 because it occurred following our departure in May (V. St.Louis, D. Muir, I. Lehnherr, K. St.Pierre, P. Aukes).

- Snowpack incubation experiments were carried out at watershed and lake sites in May to estimate transformations of mercury between inorganic and organic forms (i.e., mercury methylation) (I. Lehnherr, C. Wong).
- 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) a distinct seepage site; 2) through Skeleton Lake; 3) two smaller ponds; 4) *Carex* grass dominated wetlands; and 5) a tundra creek channel, prior to discharging into Lake Hazen. At these strategic sites, samples were taken every ~5 days for analyses of water chemistry parameters as described above for snow (V. St.Louis, D. Muir, I. Lehnherr, K. St.Pierre). We also measured water discharge from the Skeleton Lake subcatchment with a pressure transducer and gauging Skeleton Creek every five days (M. English). This provided a method for the quantification of continuous hydrologic discharge from this subcatchment into Lake Hazen. To map evaporation, water sources and the evolution of water quality, samples were collected for $\delta^{18}O$, $\delta^{2}H$-H_2O, SO_4^{2-}, and $\delta^{34}S$- SO_4^{2-} over the season from the Skeleton Lake subcatchment. Specific attention was paid to the quality and quantity of dissolved OC throughout the subcatchment, as well as over the summer season. DOC was characterized using a suite of techniques, including size-exclusion chromatography, elemental ratios, ultra-violet and visible absorbance, fluorescence scans, and $\delta^{13}C$-DOC. To determine how easily DOC degrades via natural degradation pathways, a 30-day microbial incubation and six-day photolytic incubation were conducted on DOC sampled from a seep, a wetland subsurface, and from Skeleton Lake. Finally, isotopes ($\delta^{13}C$-DIC and $\delta^{18}O$-O_2) were collected from a series of ponds and Skeleton Lake to look at in-lake and pond productivity over the summer. In addition to our work in the Skeleton Lake subcatchment, we tracked the evolution of DOC quantity and quality over the summer within five ponds on the landscape. Previous work identified differences in hydrology (evaporative versus flow-through ponds) that allow us to compare changes to geochemistry and DOC among hydrologically-different ponds.
- Further, we deployed a YSI EXO2 sonde with dissolved O_2, pH, conductivity, temperature and total algae sensors in Skeleton Lake on two occasions from 15-22 May and from 28 June to 1 August to obtain a continual record of water chemistry during both ice-covered and ice-free conditions in a productive high Arctic lake. This also included collecting samples for $\delta^{18}O$-O_2 to quantify productivity and to compare to $\delta^{18}O$-O_2 samples collected at the same time in the other landscape ponds (Lehnherr).
- Once yearly, Parks Canada and Environment and Climate Change Canada access three of the ungauged inflow rivers (Very, Abbé, Turnabout), as well as the outflow Ruggles River, by helicopter to sample for general water chemistry. We accompanied them on 15 July to collaboratively conduct added-value sampling (e.g., DOC characterization, dissolved CO_2 and CH_4 concentration and isotopes, and contaminants) on these rivers, as well as the Henrietta Nesmith River (V. St.Louis, D. Muir, I. Lehnherr, S. Schiff, K. St.Pierre, P. Aukes).
- There are two ungauged glacially-fed rivers within walking distance of the Lake Hazen base camp that we used to examine seasonal patterns in glacial runoff chemistry and loadings. Blister Creek and the Snowgoose River are representative of smaller and larger inflow rivers, respectively. We sampled these two rivers at their mouths every ~5 days from late June to early August to relate seasonal changes in glacial

discharge with chemical inputs to Lake Hazen (V. St.Louis, D. Muir, I. Lehnherr, S. Schiff, K. St.Pierre, P. Aukes). Instantaneous discharge was also measured on these two rivers throughout the sampling period (M. English, S. Schiff, P. Aukes). Glacial rivers carry high dissolved loads into Lake Hazen. We looked at the difference in δ^{13}C-DIC isotopes between filtered and unfiltered samples to better understand the effects of filtering on our final isotope values and collected samples for ^{34}S-SO_4.

- We also sampled for ^{3}H in these glacial sources (and in Lake Hazen and the Skeleton Lake subcatchment) to constrain the age and potentially source of water in Lake Hazen.
- Instantaneous flow measurements were taken on the Snowgoose River, Abbé River and Blister Creek. We will also estimate the contributions of each of the 16 input rivers to the hydrologically-gauged Ruggles River discharge outflow volume (measured by Water Survey Canada), on the basis of the drainage area of each input river subcatchment and the modeled glacial mass loss within it (M. English, M. Sharp, A. Gardner). In addition, Lake Hazen was instrumented with a pressure transducer from 25 June to 1 August to monitor lake level.

4) The metabolism of Lake Hazen itself:

- *Water column chemistry (including contaminants):* We measured freshwater quality in Lake Hazen by conducting a water column profile at the deepest point of the lake (265 m) on 27-29 July following near ice-out. We deployed a YSI EXO2 sonde with dissolved O_2, pH, conductivity, temperature and total algae sensors to determine transition zones in the water column. We sampled water using a cleaned 12 L Niskin bottle at ~15 discrete depths, sampling the upper and lower transition zones more intensely, for the complete suite of water chemistry as described above for snow, including dissolved greenhouse gases and contaminants (methyl mercury [MeHg], emerging poly- and perfluorinated alkyl substances [PFASs]). (V. St.Louis, I. Lehnherr, S. Schiff, D. Muir, K. St.Pierre, P. Aukes).
- *NPP in surface waters:* We deployed continuously measuring CO_2 (Vaisala) and O_2 (YSI EXO2 sonde) sensors in an attempt to measure net productivity in the near-shore regions of Lake Hazen surface waters. The sonde continuously monitored pH, conductivity/temperature, and total algae. Samples were collected for dissolved O_2 stable isotope (δ^{18}O–O_2) analyses to assess whole-lake metabolism by separating changes in O_2 saturation due to temperature and mixing from changes due to metabolic activity. This will be coupled with measures of δ^{13}C-DIC and δ^{13}C-POM to assess rates of net carbon metabolism. In support of these measures, we also deployed a Campbell Scientific meteorological station with an anemometer, and barometric pressure, air temperature and PAR sensors. (V. St.Louis, I. Lehnherr, S. Schiff, K. St.Pierre).
- *Sediment microbial processes and diversity:* We used UNISENSE microelectrodes (O_2, H_2S, N_2O, pH and redox) to examine microprofiles of redox-related biogeochemical processes in sediment cores collected from 50 m, 150 m and 265 m depths of Lake Hazen in May. Companion cores were sectioned at 1-cm intervals for pore water (NO_3^-/NO_2^-, NH_4^+, total dissolved P, SO_4^{2-}), and solid (N, P, C and metals) analyses. DNA was isolated from a further companion core to characterize microbial communities by targeting ribosomal small subunit genes (16SrRNA) and key processes in nutrient and contaminant cycling (such as mer-operon genes) with PCR and NGS sequencing. These samples will be used also to quantify THg profiles in the sediment and sediment accumulation rates through ^{210}Pb dating. Additional cores were taken in 2015 from Skeleton lake and Pond 1 cores. (K. St.Pierre, A. Poulain, M. Ruuskanen).

RESULTS

Below we highlight some of our major findings to date. However, analyses are still being completed for some of our activities, and results are not yet available.

1) Net exchange of energy, H_2O, CO_2 and CH4 between the atmosphere and terrestrial landscapes in the Lake Hazen watershed:

During the growing season, the dry semidesert landscape in the Lake Hazen watershed was a near zero sink of atmospheric CO_2 (-0.3±11.8 g C m^{-2}). A nearby wetland in the Skeleton Lake subcatchment accumulated over two magnitudes more carbon (58.1±20.5 g C m^{-2}) than the semidesert landscape, and was surprisingly similar to wetland NEE at much more southern latitudes (C. Emmerton, V. St.Louis).

2) Net mass change of glaciers in the Lake Hazen watershed:

We determined how to process the GPS data that will be collected in the Lake Hazen watershed with data from a station at Devon Ice Cap - which proves that the method should work and we will be able to monitor seasonal variation in vertical motion of bedrock elated to glacier accumulation/ablation (M. Sharp, B. Danielson).

Surface temperatures of glaciers in the Lake Hazen watershed have been increasing up to 0.15°C per year from 2000-2015 (M. Sharp, C. Mortimer) (Figure 1).

3) Chemical inputs to Lake Hazen from snowmelt, glacier melt and soil/permafrost thaw:

Average concentrations of NO_2+NO_3 in snowpacks collected in May 2015 on the Lake Hazen ice and on the landscape were 47 ug/L, whereas average concentrations of total phosphorus (TP) were 38 ug/L. Average concentrations of unfiltered MeHg in snowpacks were 0.36 ng/L, whereas filtered (dissolved) concentrations were only 0.15 ng/L, suggesting that a significant portion of the MeHg in snow is particle bound.

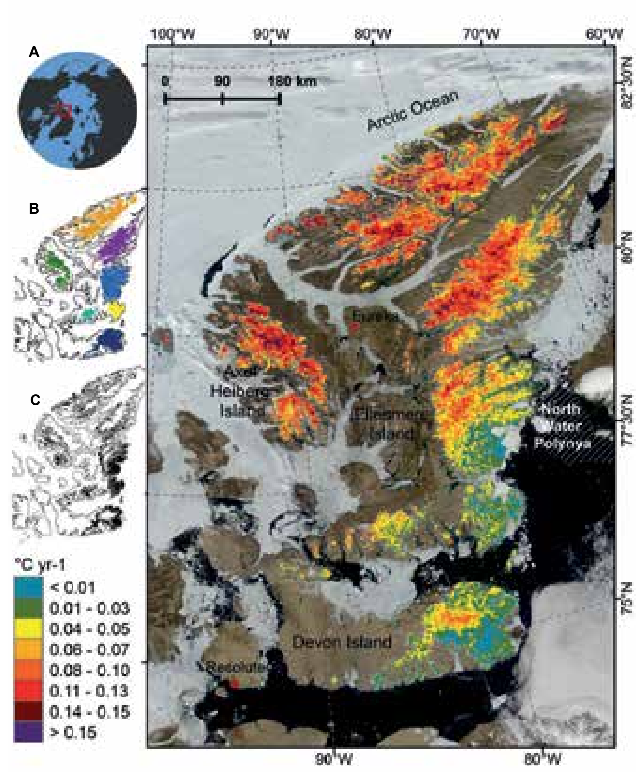

Figure 1. Changes in MODIS measured surface temperatures for all glaciers on Ellesmere, Devon and Axel Heiberg islands for the period 2000-2015.

Average concentrations of NO_2+NO_3 ranged between 37 ug/L in the Snowgoose River to 125 ug/L in the Henrietta Nesmith River. Average concentrations of TP ranged between 990 ug/L in the Snowgoose River to 1,300 ug/L in Blister Creek. The average concentration of DOC from glacial rivers was typically less than 1 mg/L. We found that average unfiltered MeHg concentrations ranged from 0.007 ng/L in the Abbe River to 0.064 ng/L in Blister Creek. Filtered MeHg concentrations were much lower and fairly consistent among the different rivers (0.007-0.014 ng/L), except in the Turnabout River (0.051 ng/L), suggesting that a significant portion of the MeHg in glacial runoff is particle bound. Both unfiltered and filtered concentrations of MeHg in the Ruggles River were lower than any of the inflow concentrations. PFASs were also detected in all of the rivers. PFASs concentration in each inflow river was higher than in the outflowing Ruggles River.

Because they were within walking distance of the Lake Hazen base camp, we were also able to sample the Snowgoose River and Blister Creek five times during the summer of 2015 to examine changes in contaminant concentrations with changing river flows.

Average concentrations of NO_2+NO_3 changed very little in the Snowgoose River and Blister Creek even though flow changed enormously. Average concentrations of TP in both rivers did change with flow, however, ranging between 220-2,403 ug/L in the Snowgoose River, and between 9-5,300 ug/L in Blister Creek, between periods of low and high flow. No trend was seen in DOC concentration over time from Blister Creek, however the small terrestrial seeps flowing into Blister Creek had a significantly higher DOC concentration (3.7 mg/L), which declined to 2.4 mg/L over the summer. Unfiltered MeHg concentrations increased from ~0.055 ng/L to ~0.150 ng/L at the height of glacial river runoff, but then declined to concentrations below 0.040 ng/L as air temperatures cooled off and river flow decreased. Filtered MeHg concentrations were consistently low at ~0.010 ng/L in both rivers. Concentrations dropped from the beginning to the end of July by a factor of 1.6-2.0 for PFASs.

We examined how water quality changed as it flowed from a soil/permafrost thaw seep through the Skeleton Lake subcatchment before entering Lake Hazen. Average concentrations of NO_2+NO_3 were 22.3 ug/L in water coming out of the seep, but were below levels of detection at all sites downstream. Average concentrations of TP in water coming out of the seep were low (2.5 ug/L) compared to those in the glacial rivers, and remained low throughout the remainder of the subcatchment (3.7-5.6 ug/L). Both unfiltered and filtered MeHg concentrations were extremely low in water initially seeping from soils/permafrost (~0.005 ng/L). Unfiltered MeHg concentrations increased as water moved through Skeleton Lake (0.075 ng/L) and two downstream ponds (0.245 ng/L). MeHg concentrations declined as water flowed downstream through the *Carex* grass dominated wetlands and the tundra creek channel prior to entering Lake Hazen at a concentration of ~0.028 ng/L. The PFAS congener profile in the Skeleton Lake subcatchment from the seep site through to the tundra creek indicated high concentrations of PFBS (the four-carbon perfluorinated sulfonate) and of PFBA. This is a unique result as PFBS was not a predominant contaminant in the glacial rivers, the Ruggles River outflow, or in Lake Hazen itself. This suggests that the seep is a specific source of PFBS into Skeleton Creek. Concentrations of PFASs declined through the continuum, suggesting PFAS sedimentation in these latter sites.

The Skeleton Lake subcatchment contained higher DOC concentrations than glacial rivers or Lake Hazen itself. Ponds on the landscape ranged from 3.8 mg/L to 24 mg/L. Concentrations of DOC within flow-through ponds remained relatively constant, while evaporative ponds increased by 3 to 5 mg/L over the summer. Along the Skeleton Lake subcatchment, we observed an increase in DOC concentration from the seep (~ 2 mg/L), to the subsurface (6 to 13 mg/L), Skeleton Lake (5.7 mg/L), and to the creek outflow (5.5 mg/L). In addition, measures of DOC composition indicate an increase in proportion of large, microbially-derived components (biopolymers) and decrease in proportion of humic substances along the subcatchment. DOC quality was assessed through a series of incubation experiments. Photolysis was responsible for the greatest loss of DOC from subsurface and Skeleton Lake samples (exhibiting losses of 0.12 and 0.06 mg-C/L per day, respectively) compared to microbial degradation. However, photolytic and microbial decomposition rates are low compared to more southerly sites. No significant loss of DOC was found in samples collected from Blister Creek or the permafrost seep.

Concentrations of SO_4^{2-} varied among the inputs into Lake Hazen. Glacial rivers (~16 mg/L) had similar SO_4^{2-} concentrations as Lake Hazen (10 mg/L).

However, the Skeleton Lake subcatchment contained significantly higher SO_4^{2-} concentrations (45 to 300 mg/L). The difference in SO_4^{2-} concentrations among inputs indicates the potential for the use of $d^{34}S\text{-}SO_4^{2-}$ to help separate sources and contributions of these distinct sources into Lake Hazen.

We are currently developing methods to analyze the age of DOC from Lake Hazen and glacial rivers. The very low DOC concentrations are challenging.

Samples for ^3H and $\delta^{18}O\text{-}H_2O$ in glacial inputs and Lake Hazen indicate that the water residence time has decreased in recent years consistent with the increased glacial melt input (Figure 2).

Numerous instantaneous flow measurements were taken on the Snowgoose River, Abbé River and Blister Creek in July 2015 (M. English, S. Schiff, P. Aukes). However, these measurements proved to be extremely challenging because these glacial rivers are very braided or completely inundated, and flow changes immensely throughout the day and season depending temperature. Melt discharge modelling results have not yet been completed (M. Sharp, A. Gardner), whereas the gauged Ruggles River discharge outflow volume measurements are still being quality controlled by Water Survey Canada.

4) The metabolism of Lake Hazen itself:

Water column chemistry (including contaminants) (V. St.Louis, I. Lehnherr, S. Schiff, D. Muir, K. St.Pierre, P. Aukes): Water column chemistry in Lake Hazen during the open water season in late July 2015 was very different from the water column chemistry previously measured under the ice in May 2013 (Figure 3). For example, following winter, we typically find that below 180 m, O_2 concentrations starts declining and CO_2 concentrations begin increasing, due to active microbial metabolism in the sediments of Lake Hazen and no physical mixing of the water column under the ice. However, in late July 2015, both O_2 and CO_2 concentrations were, for the most part, similar throughout the entire 265 m of the water column. Turbidity concentrations were ~9 times higher in the bottom waters of Lake Hazen in July 2015 than they were in May 2013. Concentrations of NO_2+NO_3 were on average 36 ug/L throughout the Lake Hazen water column, with little variation. Average concentrations of TP in the water column were 6 ug/L, ranging from below or analytical level of detection in surface waters up to 18 ug/L in the turbid bottom waters.

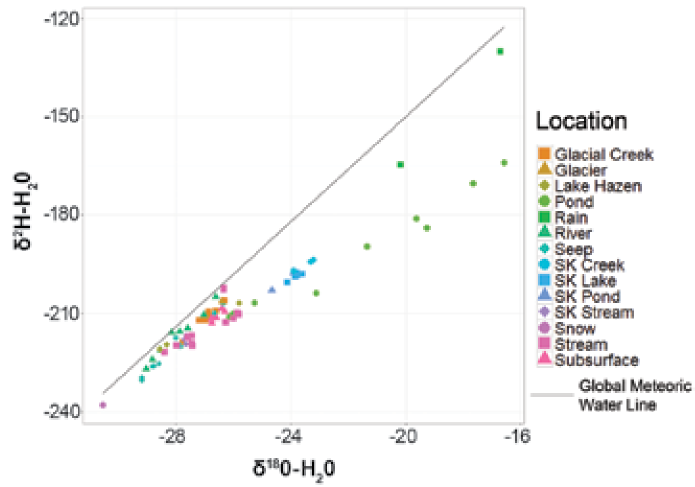

Figure 2. Water isotope values for 77 samples collected from Lake Hazen, Nunavut. Samples were collected between June and August 2015 from a glacial creek, five glacial rivers, Bridge glacier, Lake Hazen (0 m, 25 m, 50 m, 200 m, and 250 m), five ponds, permafrost seeps, two rain events, snow, small terrestrial streams, and along a hydrological continuum within the Skeleton (SK) subcatchment (permafrost seep, subsurface wetland, lake, and creek).

For contaminants, we previously found that snowmelt increased MeHg concentrations from ~0.020 ng/L to ~0.075 ng/L in surface waters during the important spring bloom of biological activity under the lake ice. Surprisingly, MeHg concentrations were extremely low (<0.006 ng/L) throughout the water column after the height of summer glacial melt and soil/permafrost thaw inputs, all of which were higher in MeHg concentration. Emerging PFAS contaminants were found throughout the Lake Hazen water column. As with MeHg, concentrations of PFASs were elevated in surface waters following the influx of snow melt water

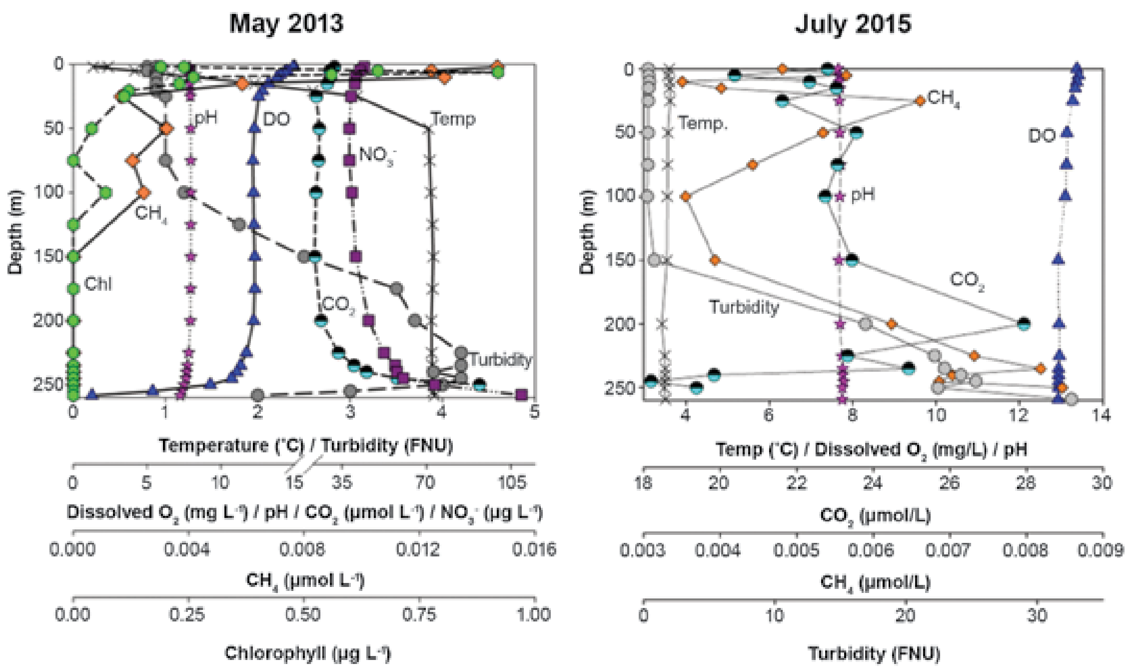

Figure 3. Profiles of physical and chemical parameters in the Lake Hazen water column under the ice in May 2014 (graph on the left) and during the open water period in late July 2015 (graph on the right).

in late May/early June. Concentrations of PFASs were at their lowest throughout the water column after the height of summer glacial melt and permafrost thaw inputs.

NPP in surface waters (V. St.Louis, I. Lehnherr, S. Schiff, K. St.Pierre): Concentrations of CO_2 in shallow waters near the shoreline of Lake Hazen were always below atmospheric equilibrium, suggesting that during the open water season, Lake Hazen is a sink for atmospheric CO_2. Oxygen concentrations were also measured continuously in these shallow waters, but these data have not yet been fully processed to the extent necessary to quantify productivity in Lake Hazen. Preliminary $\delta^{18}O\text{-}O_2$ and $\delta^{18}O\text{-}H_2O$ samples were also collected.

Sediment microbial processes and diversity (K. St.Pierre, A. Poulain, M. Ruuskanen): Oxygen was depleted within the first centimeter of all cores regardless of the depth from which the core was collected, suggesting very active microbial respiration in sediments. H_2S concentrations in the sediments were below detection. NO_2^- and NO_3^- concentrations increased in waters overlying cores collected from the deep site and decreased in throughout the core, while NH_3 concentrations increased below the sediment-water interface, suggesting active nitrogen cycling. A distinct floc layer was found at the surface of cores collected from the deep site (265 m), but was not visible at the surface of cores from more shallow depths. Despite the low quantity of DNA in sediments (high inorganic material content), all of the marker genes tested so far (16S rRNA, *glnA* and *merA*) have been amplified with PCR without problems. The mercury reductase gene merA seems to be amplifiable down to at least 27 cm from the sediment surface. 16SrRNA gene amplicons have been sequenced from the following cores: Lake Hazen 2014 (deep and shallow cores), Pond 1 and Skeleton Lake. We are currently analyzing the data and developing the bioinformatic pipelines to get a good picture of the microbial community structure and metabolism in the sediments. Genes encoding enzymes involved in N, C and S cycles will also be targeted; primer design and selection is in progress.

DISCUSSION

1) Net exchange of energy, H_2O, CO_2 and CH_4 between the atmosphere and terrestrial landscapes in the Lake Hazen watershed:

The net ecosystem exchange (NEE) of CO_2 on the semidesert landscape was most influenced by moisture, with wetter surface soils resulting in greater soil respiration and CO_2 emissions. At the wetland, soil heating enhanced plant growth, which in turn increased CO_2 uptake. We predict that until summer precipitation and humidity increases, climate-related landscape changes of dry high Arctic landscapes may be restricted by poor soil moisture retention, and therefore have some inertia against short-term changes in NEE (C. Emmerton, V. St.Louis). Conversely we need to consider the situation of where wetter soils could be inundated. In this case, we need to compare our pond productivity estimates with our terrestrial estimates of NEE.

2) Net mass change of glaciers in the Lake Hazen watershed:

Climate change is greatly enhancing glacial melt in the Lake Hazen watershed, especially since ~2007. This is resulting in up to 10 times more water and sediment loads entering Lake Hazen each year during the summer melt period than prior to 2007 (M. Sharp, B. Danielson, C. Mortimer). Further, increased glacial runoff has changed the water residence time of Lake Hazen. Thus there is a lag between Lake Hazen water chemistry and chemical inputs to the lake from glacial rivers, for example. Lake Hazen is not at steady state with respect to its inputs, and as a result, we can use this lag to understand the importance of in-lake processes.

3) Chemical inputs to Lake Hazen from snowmelt, glacier melt and soil/permafrost thaw:

Average concentrations of NO_2+NO_3 were similar in glacial river inputs to Lake Hazen, throughout the water column of Lake Hazen, and at the Ruggles River outflow of Lake Hazen. Average concentrations of TP, however, were much higher in the glacial river inputs to Lake Hazen than throughout the water column of Lake Hazen, and at the Ruggles river outflow, suggesting that a large portion of the TP entering the lake settles out on particles. Concentrations of MeHg and PFASs in the Ruggles River were lower than any of the inflow concentrations, suggesting that a combination of sedimentation, dilution and photodemethylation is occurring in the lake.

Concentrations of TP in the Snowgoose River and Blister Creek increased with increasing flow intensity, suggesting that erosional materials are the source of the TP. Filtered MeHg concentrations were consistently lower than unfiltered concentrations throughout the summer in both the Snowgoose River and Blister Creek, suggesting that a large portion of the MeHg in the rivers was particle bound and erosional in origin. PFASs concentrations dropped from the beginning to the end of July by a factor of 1.6-2.0 for PFASs, suggesting flow intensity and erosional materials do not drive PFAS loadings into Lake Hazen, and that their source is meltwater originating from more recently deposited snow and ice in glaciers.

The NO_2+NO_3 coming out of the uppermost soil/permafrost thaw seep was quickly used up downstream, suggesting that these types of subcatchments in the Lake Hazen watershed are very N-limited, and rely on efficient recycling of organic-N (e.g., DON). Average concentrations of TP in water coming out of the seep were very low compared to those in the glacial rivers, and remained low throughout the remainder of the subcatchment before entering Lake Hazen. As such, these types of subcatchments are not important sources of P to Lake Hazen. MeHg concentrations increased as water moved through Skeleton Lake and two downstream ponds, indicating that these were both sites of active microbial Hg methylation. Unlike glacial rivers, a much larger portion of the MeHg was in the dissolved phase and not particle bound, making the MeHg much more readily bioavailable for bioaccumulation in these systems. MeHg concentrations declined as water flowed further downstream, though, suggesting that MeHg was either sequestered or demethylated in these latter sites of the landscape catchment.

Lake Hazen contained low DOC concentrations (<1 mg/L), which may be representative of its primary water source: glacial rivers (DOC <1 mg/L). However, the terrestrial subcatchment contained the highest DOC concentrations. Small permafrost streams appeared to result in localized productive zones, contributing higher concentrations of DOC (2 to 4 mg/L) to surrounding creeks and rivers. Surprisingly, DOC from the subcatchment contained very little ultra-violet or visible light absorbing components. The increased proportion of biopolymers in DOC from Skeleton Lake suggest a contribution of authochthonous C to the DOC pool, which indicates increased microbial contribution along the Skeleton Lake subcatchment.

Results from incubation experiments indicate that photolysis is likely the primary driver for DOC degradation in these high Arctic environments rather than microbial degradation. However, rates are low and consistent with the lack of visible colour. This presents the possibility that these high Arctic terrestrial systems export relatively recalcitrant DOC to coastal marine environments. Furthermore, this has implications for dissolved organic nitrogen and Hg transport from these environments as they are influenced by the fate of DOC.

One hypothesis for the high concentrations of PFBS at the Skeleton Lake soil permafrost seep site is that the seep is representative of local sources due to human activity in the Park, whereas PFASs in the main glacial rivers and Lake Hazen are more representative of long-range atmospheric transport and deposition. Concentrations of PFASs declined as water moved through the subcatchment, suggesting PFAS sedimentation in these latter sites.

Instantaneous flow measurements taken on the Snowgoose River, Abbé River and Blister Creek proved to be extremely challenging because these glacial rivers are very braided or completely inundated, and flow changes immensely throughout the day and season depending on temperature (M. English, S. Schiff, P. Aukes). However, these measurements will give us some on-the-ground measurements from which to compare the melt discharge modelling results (M. Sharp, A. Gardner), as well as the hydrograph from the gauged Ruggles River outflow volume measurements taken by Water Survey Canada.

4) The metabolism of Lake Hazen itself:

Water column chemistry (V. St.Louis, I. Lehnherr, S. Schiff, D. Muir, K. St.Pierre, P. Aukes): We believe that O_2 concentrations start declining and CO_2 concentrations begin increasing below 180 m in Lake Hazen under the ice due to active microbial metabolism in the sediments of Lake Hazen, and no physical mixing of the water column under the ice. However, in late July 2015, both O_2 and CO_2 concentrations are similar throughout the entire 265 m of the water column due to a physical mixing from dense glacial river turbidity currents bringing surface river waters rapidly to the bottom of the lake. Again, turbidity concentrations were ~9 times higher in the bottom waters of Lake Hazen in July 2015 than they were in May 2013. Our few samples of $\delta^{15}N$-POM for Lake Hazen suggest that the Lake may be N limited. Indeed, there are very few N sources in this N impoverished landscape. Concentrations measured in snow and precipitation in 2015 are very low.

Concentrations of contaminants (MeHg and PFASs) throughout the water column in late July were lower than concentrations measured in May under the ice, and much lower than in river water flowing into Lake Hazen. These results suggest that these contaminants are being stripped from the water column on particles that are rapidly settling out to the bottom of the lake.

NPP in surface waters (V. St.Louis, I. Lehnherr, S. Schiff, K. St.Pierre): We now believe that concentrations of CO_2 in shallow waters near the shoreline of Lake Hazen during the summer were always below atmospheric equilibrium not because of CO_2 drawdown from primary productivity, but because of geochemical weathering of carbonate and feldspar minerals added to Lake Hazen in glacial runoff:

$$Ca_{1-x}Mg_xCO_{3\ (s)} + CO_{2\ (aq)} + H_2O_{\ (l)} \leftrightarrow (1-x)Ca^{2+}_{\ (aq)} + xMg^{2+}_{\ (aq)} + 2HCO_3^-{}_{\ (aq)}$$

$$CaAl_2Si_2O_{8\ (s)} + 2CO_{2\ (aq)} + 2H_2O_{\ (l)} \leftrightarrow Ca^{2+}_{\ (aq)} + 2HCO_3^-{}_{\ (aq)} + H_2Al_2Si_2O_{8\ (s)}$$

As a result, we will be pursuing the use of dissolved O_2 concentrations and dissolved O_2 stable isotopes ($\delta^{18}O$-O_2) analyses to assess whole-lake metabolism by separating changes in O_2 saturation due to temperature and mixing from changes due to metabolic activity. This will be coupled with measures of $\delta^{13}C$-DIC and $\delta^{13}C$-POM to assess rates of net carbon metabolism.

Sediment microbial processes and diversity (V. St.Louis, K. St.Pierre, A. Poulain, M. Ruuskanen): Again, O_2 was depleted within the first centimeter of all cores regardless of the depth from which sediments were collected in Lake Hazen, suggesting very active microbial respiration in sediments. This also suggests that there is significant amounts of organic carbon fueling this microbial respiration, the source of which we'll be pursuing in 2016 and 2017. Preliminary data from $\delta^{13}C$-DIC coupled with $\delta^{13}C$-POM suggests that the source of this sediment CO_2 flux is return of POM produced within the lake that is produced at or near the sediment-water interface. Ongoing 16S rDNA gene sequence analyses will reveal which key microbial players are present in surface sediments and whether the microbial community structure corroborates the redox gradient shown by the geochemical profile. The detection of *glnA* and *merA* at depth suggests the presence of a bacterial community that is resistant to mercury. We suggest that the mercury resistance gene is ancient and we are working at testing this hypothesis using molecular model developed in our lab.

CONCLUSION

Although it is "early days", it is tempting to speculate about changes in Lake Hazen and its watershed. There are a large number of system positive and negative feedbacks to consider. Increased glacial melt will deliver more water and sediment to Lake Hazen, decreasing the water residence time and diluting nutrients. Lake productivity may not respond to a longer ice-free season with lower nutrient inputs. Increasing runoff from the productive areas of the Lake Hazen terrestrial catchment will unlikely compensate for this increased glacial input. For the terrestrial catchment, the balance between increased precipitation may be more than compensated by increased evaporation (due to increased temperature). However, permafrost thaw may lead to increases in water availability in downslope areas, leading to increased terrestrial productivity. The water balance and thus the trajectory of arctic ponds (more or less ponds) cannot yet be predicted. Export to the nearshore marine environment will be affected by changes in the terrestrial catchment (including in lakes) but the lag will depend on water balance and storage times in the terrestrial catchment.

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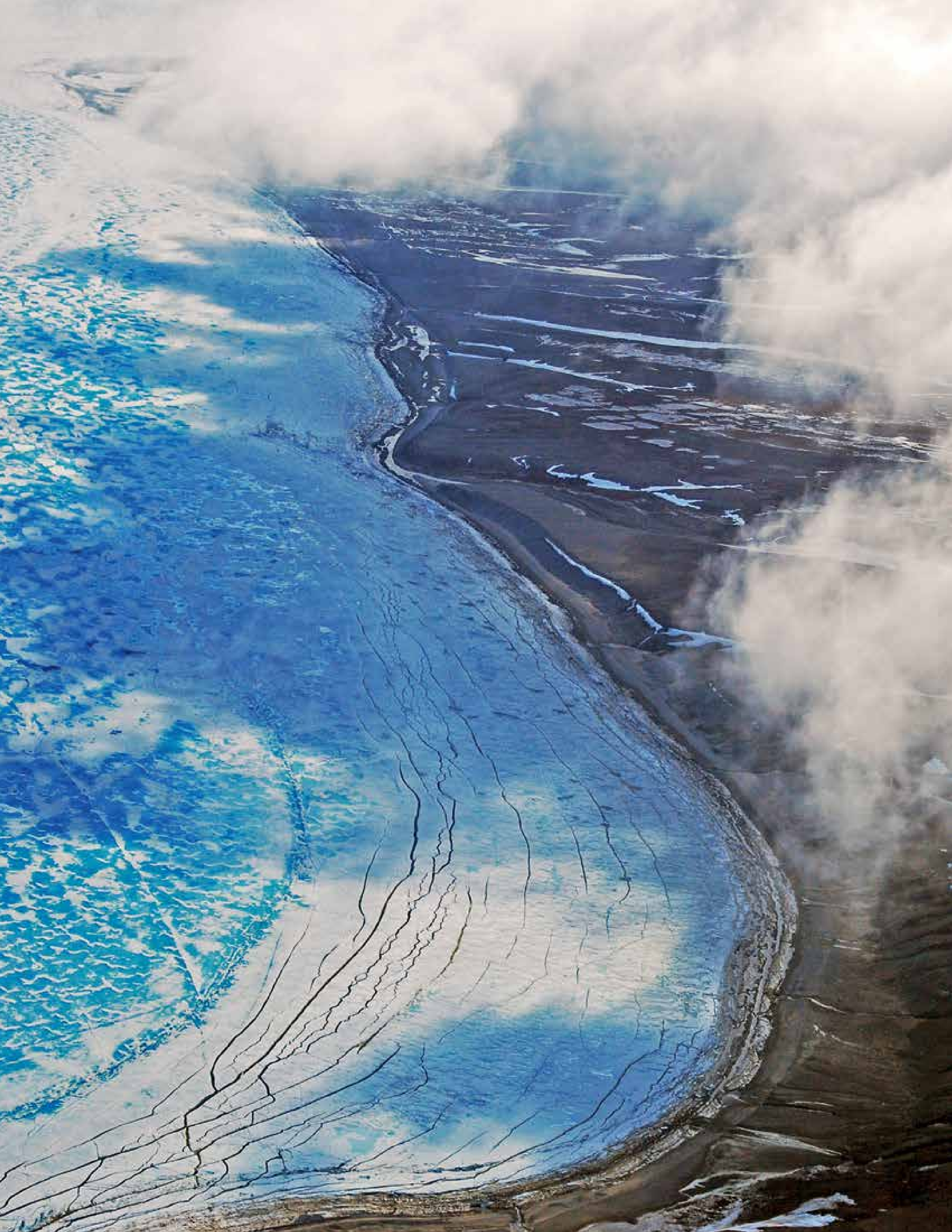

Impacts of the Changing Global Environment at Nunavut's Northern Frontier

Project Leader

Warwick Vincent (Université Laval)

Network Investigators

Dermot Antoniades (Université Laval)
Luke Copland (University of Ottawa)
Alex Culley (Université Laval)
Florent Dominé (Centre national de la recherche scientifique)
Connie Lovejoy (Université Laval)
Derek Mueller (Carleton University)
Milla Rautio (Université Laval)

Collaborator

Gregory Crocker (Carleton University)

HQP

Paschale Noël Bégin, Doctoral Student (Institut national de la recherche scientifique - Eau, Terre et Environnement)
Maria Belke Brea, Doctoral Student (Université Laval)
Sébastien Bourget, Doctoral Student (Université Laval)
Anna Crawford, Doctoral Student (Carleton University)
MSc thesis (2013): Ice island deterioration in the Canadian Arctic: Rates, patterns and model evaluation
Sophie Crevecoeur, Doctoral Student (Université Laval)
Bethany Deshpande, Doctoral Student (Université Laval)
Microbial oxygen dynamics in permafrost thaw lakes
Andrew Hamilton, Doctoral Student (University of British Columbia)
The role of ocean dynamics and meltwater input on the fate of the Milne Fjord ice shelf, glacier tongue and epishelf lake, Ellesmere Island
Henriikka Kivilä, Doctoral Student (University of Jyväskylä)
Myriam Labbé, Doctoral Student (Université Laval)
Diversity and dynamics of aquatic viruses from the Canadian High Arctic in a climate change context
Dorota Medrzycka, Doctoral Student (University of Ottawa)
Michel Paquette, Doctoral Student (Université de Montréal)
Marttiina Rantala, Doctoral Student (University of Helsinki)
Ron Saper, Doctoral Student (Carleton University)
Laura Thomson, Doctoral Student (University of Ottawa)
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Maxime Wauthy, Doctoral Student (Université du Québec à Chicoutimi)
Influence of thawing permafrost on aquatic food webs
Adrienne White, Doctoral Student (University of Ottawa)
Recent changes to sea ice, glacier ice and ice shelves in the Canadian High Arctic
Adam Garbo, Honours Undergraduate Student (Carleton University)
Abigail Dalton, Masters Student (University of Ottawa)
Michael Hackett, Masters Student (University of Ottawa)
Alice Lévesque, Masters Student (Université Laval)
Viral diversity in subarctic thermokarst ponds

Melissa Nacke, Masters Student (Dalhousie University)
Jill Rajewicz, Masters Student (Carleton University)
Jérôme Comte, Post-Doctoral Fellow (Université Laval)
Vani Mohit, Post-Doctoral Fellow (Université Laval)
Mary Thaler, Post-Doctoral Fellow (Université Laval)
Wesley Van Wychen, Post-Doctoral Fellow (University of Ottawa)
Julie Veillette, Research Associate (Université Laval)
Marie-Josée Martineau, Technical Staff (Université Laval)
Denis Sarrazin, Technical Staff (Centre d'études nordiques)
Marc-Olivier Brouard, Undergraduate Student (Université Laval)
Stephane Gagnon-Harvey, Undergraduate Student (Université du Québec à Chicoutimi)

ABSTRACT

Global climate models predict that the greatest warming effects of greenhouse gas accumulation in the atmosphere will be at the highest latitudes of the Arctic, and consistent with these projections the High Arctic appears to be warming at rates well above the global mean. Over the first three cycles of ArcticNet, we have established observatories at Ward Hunt Island and along the adjacent northern coastline of Ellesmere Island: Nunavut's northern frontier. These sites have proven to be strategic research locations for detection and analysis of environmental change given the diversity of ecosystems in this region, their extreme sensitivity to perturbations of the cryosphere (snow and ice-containing environments), and the current trend of accelerated warming at these far northern latitudes (82-83N). For Phase 4 of ArcticNet, we have assembled a team of eight research laboratories with complementary expertise to evaluate climate change and its effects, with emphasis on the cryosphere (snow, ice and permafrost) and aquatic environments (lakes and fiords) of this coastal Arctic region. Our specific objectives include application of ArcticNet monitoring protocols for climate, snow and permafrost ground temperatures; development of a new indicator of climate change (snow thermal conductivity); analysis of changes in the Milne Ice Shelf and its associated ecosystems; mapping of the surface motion of northern glaciers and estimates of their mass balance (including the longest record for Canada); analysis of the timing, size and duration of shore and flaw leads; tracking of the ice islands that have originated from northern Ellesmere Island and NW Greenland, and modelling of their drift and decay as marine hazards; analysis of lake and fiord sediments to determine long term climate variability; biodiversity analysis of the network of microscopic life (including viruses) that supports northern aquatic ecosystems; and new measurements of aquatic food web structure, including by way of novel imaging techniques. Our overarching aim is to produce a subregional IRIS of northern Ellesmere Island that will be nested within a broader regional impact study (IRIS-2 of ArcticNet), and that will contribute to international, circumpolar initiatives that are currently underway or proposed.

KEY MESSAGES

- The northern coastline of Ellesmere Island, at Nunavut's northern frontier, contains diverse ice features and ecosystems that are vulnerable to global change.
- Our work has revealed a rich microbial community and associated food web in Nunavut's most northerly lake (and thus the most northerly in Canada): Ward Hunt Lake.
- This lake is undergoing rapid transition, from more than 4 m of ice cover in the 1950s, to rapid thinning and loss from 2008 onwards; despite recent years of relatively cool summers, there is no evidence of a return to thick ice conditions.
- Viruses are an abundant, dynamic and important component of the microbial community of aquatic environments yet they remain relatively understudied in the lakes and coastal marine waters of the Canadian High Arctic.
- Critical under-ice ecological processes and winter trophic interactions have year-round repercussions on primary productivity and food availability for higher trophic levels.
- The species composition and productivity of organisms in the lakes in the Canadian High Arctic is responding to the changes related to ice cover.
- The rapid recent breakup of Yelverton Glacier has produced the majority of the > 2500 icebergs currently present in Yelverton Inlet and Bay.
- Iceberg production rates from tidewater glaciers can be highly spatially and temporally variable due to the influence of glacier surging.
- With collaborators, we are developing techniques to conduct high-precision survey ice islands and icebergs both above and below water.
- We have developed, tested and deployed an ice island thickness measurement system in Baffin Bay.

- Our work revealed an unexpected seamount in the middle of Milne Fjord that may act to stabilize the Milne Ice Shelf.
- We discovered an outflow channel beneath the Milne Ice Shelf and we have instruments in place to measure the velocity and salinity of this water.
- Our calibration work shows that traditional stake measurements provide an effective way to measure glacier mass balance when compared to geodetic measurements of changes in ice surface elevation over time.

OBJECTIVES

We addressed all Year 1 objectives as described in the proposal:

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. Make new and ongoing cryospheric observations to determine changes in the Milne Ice Shelf (including the under-ice water flow), lake ice and alpine glaciers along the northern coast of Ellesmere Island.
4. Map surface motion for all glaciers and ice caps in northern Nunavut and its temporal variations.
5. Apply long term (since 1959) monitoring methods to determine the mass balance of White Glacier, Axel Heiberg Island, and to evaluate the climate-related mechanisms affecting glacial flow.
6. Evaluate the timing, size and duration of shore and flaw leads along the northern coast of Ellesmere Island from 1999 to present and relate these to pack ice motion and meteorological variables.
7. 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).
8. Improve the understanding of the variability in northern Ellesmere Island climate over the last 5000 years by way of paleolimnological analyses of sediments from northern lakes and fiords.
9. Define the water column properties, including plankton, of lakes and fiords along the northern Ellesmere Island coastline, the physical dynamics of these waters, and the year-to-year and long-term changes.
10. Determine the microbial networks that underpin northern lake and fiord ecosystems, with attention to the molecular biodiversity of viruses and protists that likely control carbon fluxes and energy flows.
11. Make new measurements of the food web structure of northern lakes and fiords, with emphasis on zooplankton, benthic invertebrates and comparative measurements at Resolute and Cambridge Bay.
12. Apply imaging, molecular, microscopy and biogeochemical techniques to analyze the photosynthetic communities that occur on the bottom of Nunavut lakes, with comparisons in Nunavik lakes.
13. Develop novel methodologies for monitoring sub-ice biota, including video and automated systems.
14. Synthesize all available and pertinent information concerning northern Ellesmere Island in the form of a sub-regional IRIS that can be used in ArcticNet, AMAP and other climate assessments.

INTRODUCTION

Global climate models predict that the greatest warming effects of greenhouse gas accumulation in the atmosphere will be at the highest latitudes of the Arctic, and consistent with these projections, the High Arctic appears to be warming at rates well above the global mean. Over the last 10 years, we have established a set of observatories along the High Arctic coastline at the northern limit of Nunavut, in Quttinirpaaq National Park and adjacent areas: Nunavut's northern frontier. These sites have proven to be strategic research locations for detection and analysis of environmental change, given the diversity of terrestrial, freshwater and marine ecosystems in this region, their extreme sensitivity to perturbations of the cryosphere (snow and ice-containing environments), and the current trend of accelerated warming at these far northern latitudes (reviewed in Vincent et al. 2009, 2011). The central objective of this project is to evaluate climate change and its effects on the Northern Ellesmere coastal environment, with emphasis on the cryosphere (snow, ice, permafrost) and aquatic environments (lakes, fiords), and to make comparative measurements on lake, snow and ice systems (including icebergs and glaciers) further to the south.

The cryosphere is responding to recent changes in climate. Snow is a critical and ubiquitous environmental compartment of high latitude regions and its physical properties strongly impact the energy budget of the surface and of the ground. Snow physical properties are largely determined by meteorological conditions, which govern snow metamorphism, i.e. recrystallization processes of snow crystals due to changing thermodynamic variables. With climate change, snow physical properties are expected to change and to feedback on climate. Ice shelves of northern Ellesmere Island have substantially changed over the last decade. A lack of regeneration suggests that ice shelf loss is irreversible (Copland et al., 2007; White et al., 2015), after being in place for millennia (Antoniades et al., 2011; England et al., 2008). 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. 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) 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.

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). Planktonic and benthic microbial communities often dominate these high latitude ecosystems but they are still not very well characterized. In particular, wild viruses play a critical yet understudied role in the Arctic microbial communities. Our research addresses the biodiversity, structure and dynamics of these high latitude microbial food networks.

ACTIVITIES

Field work

The 2015 field work season along the northern coast of Ellesmere Island was extremely successful and all objectives were completed as planned. Data are now being uploaded into Nordicana D, with cross-referencing in Polar Data Catalogue. Additionally, sampling was undertaken at Cambridge Bay in June (Lovejoy and Rautio labs) and September (Vincent lab), and included some training of CHARS personnel in lake and permafrost sampling. Fieldwork for ice islands has also been undertaken in Baffin Bay and off Newfoundland.

- A field camp was established at Purple Valley (rear of the Milne Ice Shelf) for approximately a week in July 2015 to service existing weather stations and time-lapse cameras on the Milne Ice Shelf.
- We downloaded our Ward Hunt Island climate stations plus our satellite stations at Lake A and Lake C1 on Ellesmere Island in July 2015.
- We continued our long term measurements of permafrost monitoring and automated cameras on Ward Hunt Island in July 2015, including a new installation on our 10 m tower overlooking the snow monitoring site.
- We have deployed instruments on Ward Hunt Island (July 2015) to monitor the thermal conductivity of snow. Snow thermal conductivity is measured with heated needle probes and three needle probes were positioned on a post at heights of 2, 8 and 14 cm (Figure 1). These will allow the measurement of the thermal conductivity of the expected basal depth hoar layer (at 2 cm) and of the top wind slab (at 14 cm). The middle probe will constrain the height of the boundary between both layers. We will obtain the first year of data during May 2016.
- Time-lapse cameras were downloaded and serviced to provide monitoring of the Milne Glacier and floating ice tongue, and to monitor ice shelf breakups in our absence.

Figure 1. Post holding the three heated needle probes at heights of 2, 8 and 14 cm and the three thermistors at heights of 0, 6 and 12 cm. Cables linking the instruments to the data logger have been buried to protect them from wildlife. (Photo by Denis Sarrazin).

- We recovered, maintained and redeployed instruments that have been recording temperature and salinity continuously in Milne Fiord since May 2011 (Figure 2).
- Ice-penetrating radar was used to survey the outflow channel at the seaward edge of the Milne Ice Shelf. We were able to access the water-column in the channel at two places and conduct several CTD casts and profile current velocity. One site was instrumented with an upward looking Acoustic Doppler Current Profiler (ADCP) and several conductivity loggers.
- We conducted CTD and turbidity profiles at the grounding line of the Milne Glacier to track subglacial inflow of meltwater. We serviced a small ablation stake network on the Milne Glacier and floating ice tongue and downloaded temperature loggers at each stake.
- A helicopter survey was undertaken along the length of Yelverton Inlet and Bay, northern Ellesmere Island, to provide a comprehensive inventory of the icebergs and ice islands in this region, and to provide validation for Landsat, Radarsat and

Figure 2. MSc student Jill Rajewicz making a CTD profile of the epishelf lake in July 2015. This oceanographic mooring has been monitoring Milne Fiord since May 2011 is on the left. (Photo by Adam Garbo).

Sentinel satellite imagery that was acquired nearly simultaneously with the field survey.

- Iceberg thicknesses were measured with a portable ground-penetrating radar system.
- Speckle tracking of pairs of Radarsat-2 images was used to determine ice motion patterns across the study area, and their variability over time.
- Fieldwork was undertaken for approximately three weeks on White Glacier and nearby tidewater calving glaciers, Axel Heiberg Island, in July 2015, to monitor ice motion and iceberg calving patterns.
- Fieldwork was undertaken on White Glacier for two weeks in May 2015 to continue the long-term mass balance record there and to service existing weather and GPS stations.
- A new automated snow depth sounder was installed in the accumulation area of White Glacier, to provide the first continuous snow accumulation measurements. This will help to address questions such as whether there is summer snow accumulation that is not accounted for in regular mass balance stake measurements.
- Three new high resolution SLR time-lapse cameras were installed overlooking glaciers on western Axel Heiberg Island to provide better understanding on the patterns and distribution of iceberg production to the ocean in this region.
- In October, we deployed an automated ice island thickness monitoring system in Baffin Bay. This consisted of a stationary ice penetrating radar and weather station with a webcam. Both of these are programmed to telemeter data via Iridium satellite (Figure 3).
- In April, we deployed beacons on five icebergs and one large ice island off the coast of Newfoundland during the joint Statoil-ArcticNet cruise. We used the helicopter to conduct structure-from-motion photogrammetry mapping of five of these icebergs, we surveyed four icebergs using a scanning Lidar and with G. Joyal and J-G. Nistad we surveyed the underwater portion of one iceberg, using multibeam sonar.
- We undertook physico-chemical profiling of the water column of Ward Hunt Lake, Lake A and Milne Fiord (Neige Bay) in July 2015.
- Water samples from these three sites were collected at different depths for nutrient, pigment, microscopic and molecular analyses in order to assess viral and microbial diversity. DNA analysis is now in progress (Figure 4).
- Pre-filtered water from these lakes was used in experiments by the Culley Viral Ecology Laboratory to inoculate cyanobacteria cultures previously

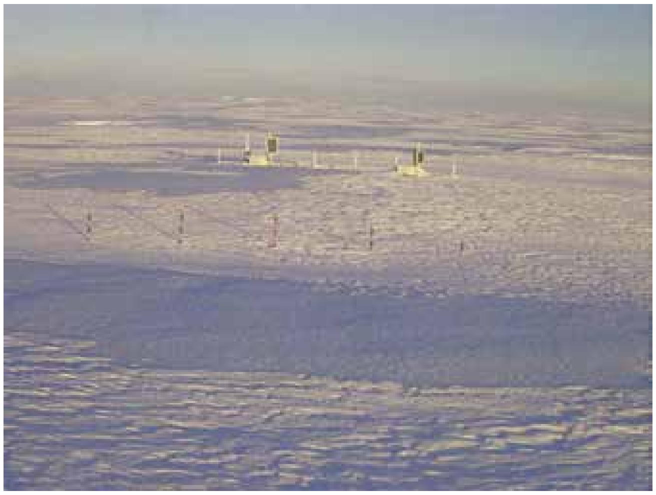

Figure 3. A view of the automated ice penetrating radar on ice island PII-A-1-f near Qikiqtarjuaq taken by the webcam on an adjacent climate station.

Figure 4. Collecting wild virus samples from Neige Bay, Milne Fjord. (Photo by Denis Sarrazin).

isolated from the High Arctic by the Vincent Laboratory (U. Laval) (Figure 5).

- For the lake food web aspect of this project, sediment and water samples were collected from Lake A and Ward Hunt Lake in July 2015 and a comparative sampling campaign was carried out at Greiner Lake near Cambridge Bay (Figures 6 and 7) in the spring and summer of 2015. The aim of this sampling strategy is to provide a baseline description of the ecological variability of the trophic structure, biomass and health, in order to better estimate the resilience of these systems. Similar comparative measures were carried out in Kuujjuarapik, Northern Quebec. In total, more than 30 lakes and ponds have been sampled for water chemistry, plankton, food webs and watershed-lake coupling indicators.

2015 milestones

Major progress was made relative to each of the 2015 milestones, as described in the original proposal (publications and communications are all listed in the “Publications” section):

- Organize the Freshwater Synthesis symposium at ICARPIII (Japan) including presentation of new northern Ellesmere Island freshwater results (Vincent is lead convener of this session; April 2015).

This went extremely well and included two oral presentations from our ArcticNet team and collaborators (Vincent et al. 2015; Sjöberg et al. 2015) as well as a poster (Bégin et al. 2015). In addition, ArcticNet student Paschale Bégin co-organized a discussion session for early career researchers on future priorities for Arctic freshwater research. This has resulted in a questionnaire that has been disseminated internationally.

- ArcticNet ‘Nunavut Northern Frontier’ kick-off meeting at CEN, ULaval, Québec City by (31 May 2015).

This was undertaken on 7 May 2015 as planned, with all PIs present.

- Contribute to a Freshwater Synthesis review paper; meet with international IASC and INTERACT collaborators (31 May 2015).

This meeting took place at ICARPIII, and the Arctic Freshwater Synthesis paper is currently under revision with the Journal of Geophysical Research.

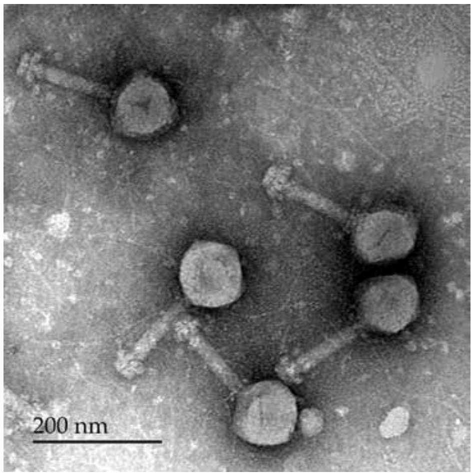

Figure 5. A tailed phage that infects a High Arctic strain of cyanobacteria.

Figure 6. Making holes through 200 cm thick ice in Greiner Lake in Cambridge Bay. (Photo by Milla Rautio).

Additionally, an INTERACT freshwater overview chapter in a book for dissemination to the public was published (Vincent and Paavola 2015), as well as a review synthesis of polar desert catchments such as those in Nunavut (Pointing et al. 2015), drawing attention to the importance of cyanobacteria and other microscopic photosynthetic organisms in these environments.

- Present Nunavut glacier change results at the International Glaciological Symposium on Hydrology of Glaciers and Ice Sheets, Hofn, Iceland (1 July 2015).

This meeting conflicted with a summer field course and the results were therefore presented at the 'Ilulissat Climate Days' meeting in Greenland instead.

- Publish high resolution map of surface motion for all glaciers and ice caps in northern Nunavut, and its temporal variability over the past 15 years (1 Dec 2015).

This was published in January 2016 (Van Wychen et al. 2016).

- Northern Frontier team meeting and consultation with northern, national and international partners, and IRIS meetings at the ArcticNet Annual Scientific Meeting (10 Dec 2015).

The Northern Frontier group met in Vancouver as planned.

- Publish Ward Hunt Lake ice synthesis (50 year record) and water track papers (31 Dec 2015).

The lake ice synthesis paper was published (Paquette et al. 2015), and the water track paper is now in advanced manuscript stage (Paquette et al. 2016).

- Publish the multidisciplinary synthesis of knowledge about northern Ellesmere Island Ice Shelves, in a book edited by Copland and Mueller (31 March 2016).

This book should be in press by then or nearly so (now submitted for copy-editing) (Copland and Mueller 2016).

Figure 7. Sampling Greiner Lake sediments. (Photo by Milla Rautio).

- Compile and publish Milne Fiord ice shelf and under ice hydrographic data (31 March 2016).

It will be compiled but not submitted for publication by then.

- Publish ice melt model and Petersen Bay hydrography papers (31 March 2016).

The Petersen Bay hydrography paper is now published (White et al. 2015). A BSc student is working on a temperature index melt model for Milne Glacier and he hopes to publish this in the summer 2016.

RESULTS

Climate monitoring

- Ward Hunt Island experienced unusual clear sky conditions during most of the period of sampling, which may have led to accelerated snow and ice loss.
- Weather conditions were extremely warm in Purple Valley in July 2015, with temperatures reaching almost 20°C in the mountains surrounding the Milne Ice Shelf. Clear sky conditions during this period resulted in strong inversions, and consequently large snow losses from the accumulation areas of glaciers.

Cryosphere

a) Ward Hunt Island

- It was unlikely that Ward Hunt Lake or the other lakes lost their ice cover in 2015, and despite multiple preceding years of cool conditions (in contrast to the period 2000-2012) there was no evidence of a return to thick ice covers. The summer ice on Ward Hunt Lake was around 2 m, still well below the 4.3 m ice recorded in the 1950's, and as compiled in our article Paquette et al. (2015) (Figure 8).

b) Milne Fiord

- We discovered a 1-2 m s^{-1} jet of brackish water at about 8 m depth in the purported outflow channel in the Milne Ice Shelf. This is consistent with our hypothesis that the epishelf lake drains through at least one channel in the Milne Ice Shelf.
- We have generated a 3D map of a section of this channel from ice-penetrating radar data. This will be further analyzed to determine the cross-sectional area of the channel (to permit discharge calculations) and to examine the glacio-fluvial geomorphology of this inverted valley.
- We discovered a sea mount under the Milne Ice Shelf and suspect that the ice shelf may be grounded

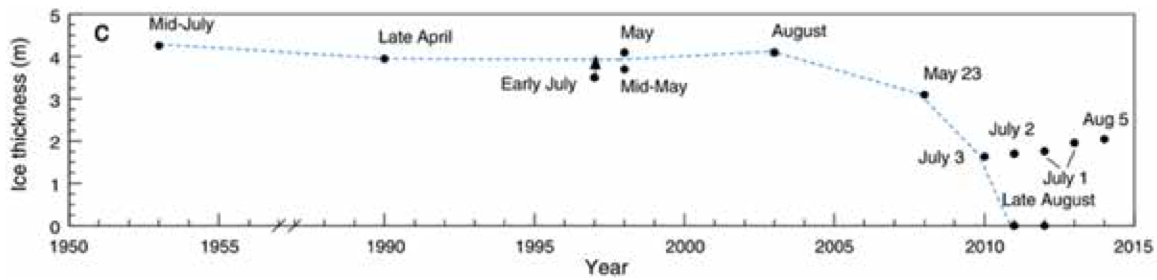

Figure 8. Ward Hunt Lake ice thickness, annotated with the date of measurement. Note the break in the x axis due to the absence of data (Paquette et al. 2015). © 2015 John Wiley and Sons, © 2015 Paquette, Fortier, Mueller, Sarrazin, Vincent.

on this point. This has major implications for fiord circulation and the stability of the ice shelf.

- Our ablation stakes indicate the lower reaches of the Milne Glacier and Milne Glacier ice tongue have lost 1100 kg m^{-2} of ice, on average.
- The iceberg work in Yelverton Bay and Inlet identified a total of 2602 icebergs, covering a total area of 59.3 km^2. The majority of these icebergs appear to have originated from the almost 10 km long floating terminus of Yelverton Glacier (Figure 9).
- An inter-comparison of different satellite image sources with field observations indicated that Landsat 8 imagery is the far superior method for detecting icebergs in summer conditions, detecting a total of 2602 icebergs compared to 134 for Sentinel-1 imagery and 69 for Radarsat-2 imagery. The Landsat 8 imagery is particularly good at detecting small and medium size icebergs (i.e., those <120 m in length), which are not visible at all in Sentinel-1 and Radarsat-2 imagery.
- Helicopter landings on icebergs in Yelverton Inlet indicated thicknesses ranging between 94.2 and 168.2 m (Figure 10).

c) White Glacier

- A new high-resolution map and digital elevation model of White Glacier was produced using the Structure from Motion method with >400 air photos (Figure 11).
- Long-term negative mass balance conditions at White Glacier continued in 2015. A comparison of the new digital elevation model of the glacier with a 1960 map indicates a mean mass loss of 9.61 m water equivalent between 1960-2014. There is no statistical difference between this value and the mean mass loss of 11.50 m water equivalent measured using traditional stake measurements over the same period. This indicates that field measurements provided an excellent record of mass balance conditions on an annual timescale. A paper will shortly be submitted to Journal of Glaciology describing these results.
- The Radarsat-2 speckle tracking measurements indicate that glacier velocities in the study area average ~100 m a^{-1}, but reach >500 m a^{-1} on glaciers such as the Otto during surges. An analysis of variability in glacier velocities since 1999 indicates that glacier surging is relatively common across the study area, and that subglacial sills may play an important role in regulating ice motion near glacier termini (Van Wychen et al. 2016).

d) Ice Islands

- Newfoundland: Our analysis of repeat structure-from-motion point clouds of the same iceberg indicated that the error associated with this technique can be very low depending on the type of GPS tracking unit that is deployed to correct for iceberg drift during the survey. We wish to

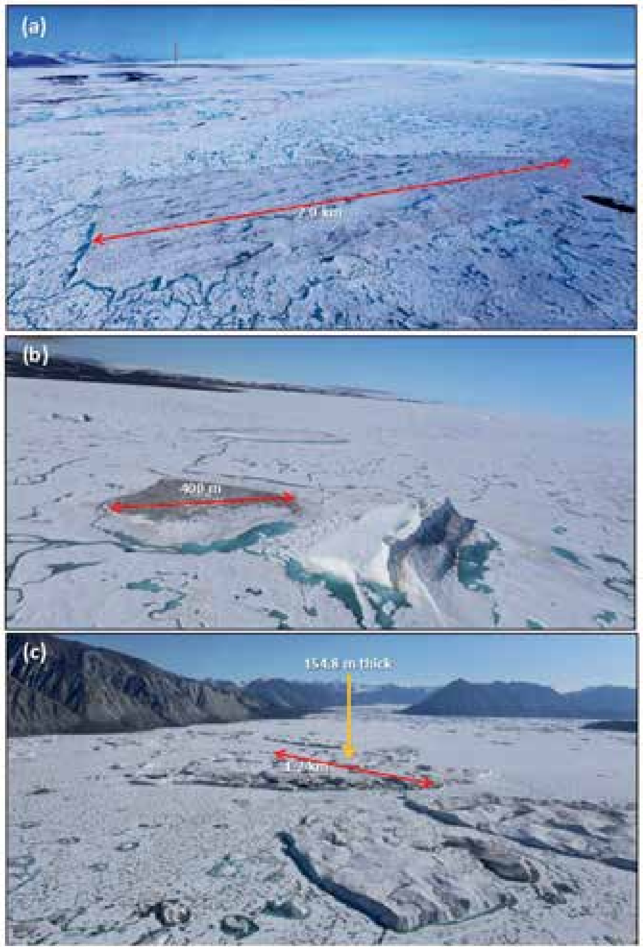

Figure 9. Examples of very large icebergs observed during helicopter overflights on 13 July 2015; a) at head of Yelverton Bay; b) in SW corner of Yelverton Bay; c) in southern Yelverton Inlet. Thickness measurements made by GPR.

examine the pattern of deterioration over time with repeat surveys, so a low error implies small amounts of deterioration could be detected in future studies. A standard GPS yields a relatively high (0.43 m) inter-survey registration error and could potentially detect local melt or calving over 3.4 m with 95% confidence versus high-precision GPS units which gives low (0.18 m) inter-survey registration error and would detect local deterioration over 0.55 m with 95% confidence.

- Baffin Bay: Our climate station and automated ice-penetrating radar system have been reporting without interruption since deployment in October. There were issues with the radar signal for a period of about 10 days in January but these have since been resolved. The ice thickness has remained constant at about 110 m.

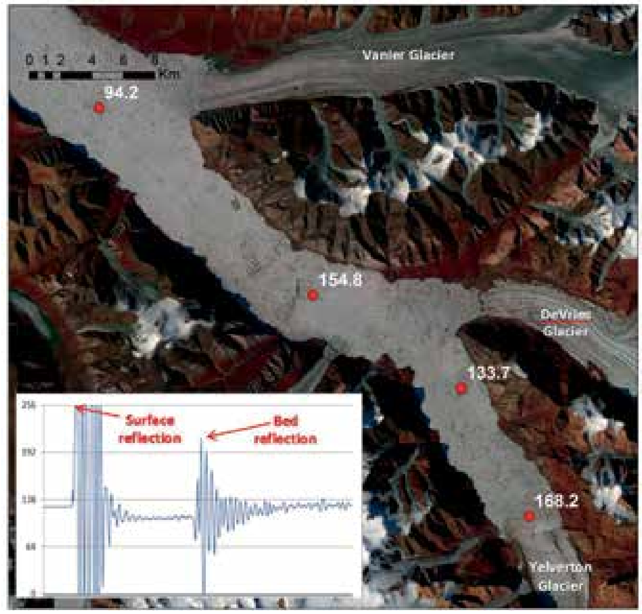

Figure 10. Thicknesses of icebergs measured in Yelverton Inlet on 13 July 2015. Inset: examples of a 10 MHz GPR trace recorded on the southernmost iceberg. Base image: Landsat 8, 12 July 2015.

Limnological and paleolimnological measurements

- An overflight was made of the Stuckberry Point/ Doidge Bay region, which confirmed the presence of lakes with different extents of ice cover, from open water to completely frozen; we would like to sample these waters in future years, given their gradient of ages and limnological conditions.

Microbial network characterization

- All sampling was completed for microbial DNA analysis. Our ArcticNet postdoc continued to develop and apply protocols for microbial network analysis, and our first paper with this

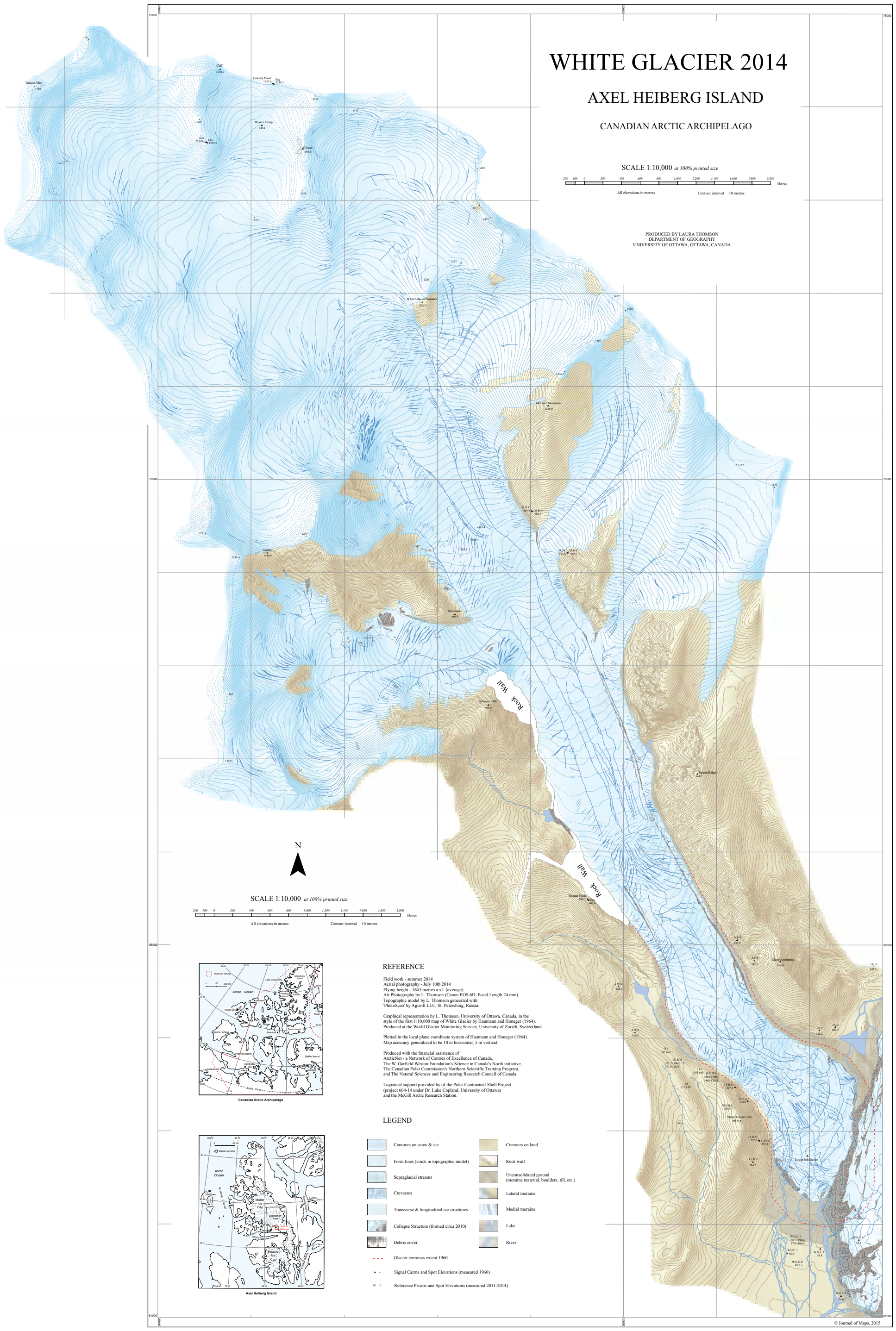

Figure 11. High-resolution map of White Glacier (Thomson and Copland 2016). © 2016 Laura Thomson.

methodology was published in January 2016, focused on Nunavik permafrost lakes: Comte et al. (2016). Jérôme Comte is now analyzing the molecular data from Ward Hunt Island and this is moving into manuscript form.

Viral analysis

- Our experiments are still ongoing and thus we are unable to ascertain fully whether the objectives of the project have been attained. Nevertheless, we successfully executed our sampling strategy. In addition, preliminary data from our efforts to isolate viruses from these environments are encouraging but where challenged by cultures exhibiting lower levels of auto-fluorescence, restrained growth and drastic changes in coloration relative to the controls.
- The inoculum of cyanobacteria cultures have resulted in several candidate viruses, which we are now propagating further to increase the virus yield. In the next few months we will amplify, purify and sequence all viral isolates

Lake food web analysis

- Phytoplankton biomass was low and made of highly variable taxa.
- The number of species and the biomass of zooplankton were high especially in the ponds that are too shallow to harbour fish (the main predators of zooplankton). The zooplankton was also highly pigmented, possibly as a response to ozone depletion and high solar ultraviolet exposure (Figures 12 and 13).
- Zooplankton has the highest percentage of lipids per unit mass, followed by seston, benthos, terrestrial vegetation and soils. These results will be combined with stable isotope signatures of the samples and carbon quality in each source habitat to estimate food web structure and diet sources of zooplankton and other aquatic organisms.
- The preliminary results of carbon quality (high values of SUVA and CDOM: indicators of the presence of terrestrial carbon in lakes) show that the land-lake coupling is stronger in ponds with terrestrial carbon sources likely playing an important role in aquatic food web ecology.
- Copepods, mysids and benthic invertebrates contain the highest amount of lipids but according to the PUFA content, the mysids make the best fish food, followed by stickle backs and benthic invertebrates.
- Chironomid larval exoskeletons were collected in the water column and we observed chironomid tubes in the mid-lake sediments of Ward Hunt Lake. These insects may spend their larval stages in the sediments and then move all the way up in the water column and through the ice candles for their adult aerial stage.
- Our preliminary analysis of the zooplankton samples revealed the presence of rotifers in Ward Hunt Lake (*Keratella hiemalis, Polyarthra* sp., *Rhinoglena* sp.). A copepod nauplius was also found in a sample, suggesting there may be a small population of copepods; however, no adults were observed. The copepods *Drepanopus bungei* and *Limnocalanus macrurus* were identified in Lake A, as previously reported.

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, and this now houses important ArcticNet data sets, cross-referenced in the Polar Data Catalogue. We are especially pleased that Nordicana D's application to be an internationally recognized doi-based repository was accepted by the international consortium of publishers COPDESS, and that ArcticNet's Nordicana D data sets are now being cited in journals such as

Figure 12. Underwater photo of a bottom of ponds showing the thick layers of benthic algae growing on rocks and soft sediment. Notice also the red zooplankton.

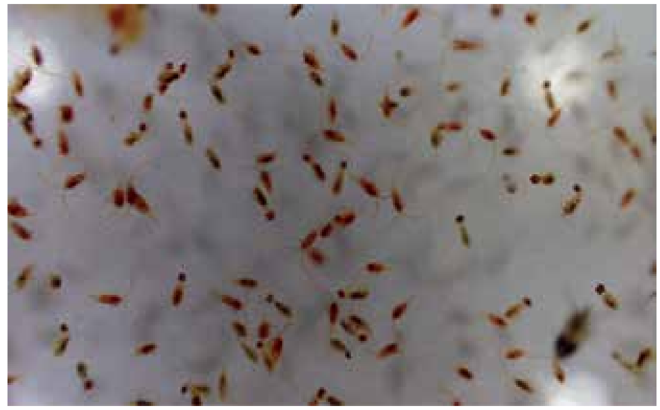

Figure 13. Calanoid copepods carrying eggs. The red color comes from photoprotective astaxanthin pigment.

those published by the European Geophysical Union, the American Geophysical Union and John Wiley & Sons Inc.

- As a satellite to the Polar Data Forum at University of Waterloo, we ran a well attended data workshop at Centre d'études nordiques (CEN): "Meeting the Data Challenge: Data initiatives and opportunities for northern environmental sciences", 26 Oct. 2015 (Figure 14).
- ArcticNet postdoc Mary Thaler worked with colleagues in the Lovejoy Northern Frontier laboratory to finalize the first version of a reference DNA data base that can now be used to identify micro-organisms in Nunavut marine and freshwaters. This important resource has now been published in Nordicana D: Lovejoy et al. (2015), and is already being used and cited. An updated version is planned for 2016.

DISCUSSION

Snow thermal conductivity data, together with meteorological data already being monitored on site, will be used to simulate snow properties, heat exchanges between the atmosphere and the snow and the ground thermal regime. Long term monitoring will allow the detection of changes in snow properties and simulations will help determine how these changes feedback on climate. Negative mass balance conditions for glaciers and ice shelves continued across the study area in 2015. Also, ice shelf breakups are continuing; for example, the Petersen Ice Shelf has continued its recent disintegration (White et al. 2015), and by the end of summer 2015 it had reduced in area by approximately 2/3 compared to a decade earlier. Large numbers of icebergs are currently present along northern Ellesmere Island, with several of them >1 km in length. These may present a risk to shipping and offshore oil exploration in areas such as the Beaufort Sea in future years. Radarsat-2 imagery provided an effective way to determine regional ice motion and iceberg production rates. New work has recently started to investigate the detailed processes that control iceberg calving patterns at glacier termini using >5000 Radarsat scenes obtained from the Canadian Ice Service. We have advanced our knowledge of the key features and processes that act to preserve or degrade the ice shelf, epishelf lake, floating glacier tongue and glacier in Milne Fiord. We are developing 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 data set

Figure 14. The CEN-ArcticNet-INQ data workshop program.

will be combined and analyzed collectively to provide a comprehensive understanding of how changing ice and snow conditions affect the biodiversity and productivity of high-latitude planktonic communities.

CONCLUSION

Our research on the snow, glaciers, icebergs, lake ice, ice shelves, permafrost, lake waters and northern fiords is leading to 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 rich mosses and microbial life that coat the bottom of Ward Hunt Lake, and the diverse 'wild viruses', that occur in all of the waters. This work is also deepening our understanding of the Nunavut cryosphere and its potential responses to global climate change, which is proceeding rapidly at these high northern latitudes, and in some cases creating new ice-hazards for maritime industries. Not only are these changes at Canada's Northern Frontier important to track and understand for the people of Nunavut, but they are also of vital concern to all human society as sentinels of how fast our planet Earth environment is changing.

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SECTION III. INUIT HEALTH, EDUCATION AND ADAPTATION

Section III is composed of eight ArcticNet research projects covering many components of human health, housing and education under adaptation perspectives of climate change and modernization.

Designing and Implementing the Nunavik Health Survey Qanuippitaa 2016

Project Leader

Pierre Ayotte (Université Laval)

Network Investigators

Belkacem Abdous (Université Laval)
Richard Bélanger (Université Laval)
Christopher Fletcher (Université Laval)
Christopher Furgal (Trent University)
Mélanie Lemire (Université Laval)
Benoit Lévesque (Centre de Recherche du Centre hospitalier de l'Université Laval)
Michel Lucas (Centre de Recherche du Centre hospitalier de l'Université Laval)
Gina Muckle (Université Laval)
Mylene Riva (Université Laval)

Collaborators

Peter Bjerregaard (National Institute of Public Health - Denmark)
Laurie Chan (University of Northern British Columbia)
Gérard Duhaime (Université Laval)
Emily Jenkins (University of Saskatchewan)
Patrick Leighton (Université de Montréal)
Jean-François Proulx (Nunavik Regional Board of Health and Social Services)
Torkjel M. Sandanger (UiT - The Arctic University of Norway)
Bouchra Serhir (Institut national de santé publique du Québec)
Hope Weiler (McGill University)
Cédric Yansouni (McGill University Health Centre - Research Institute)

HQP

Myriam Fillion, Post-Doctoral Fellow (University of Ottawa)
Abdullah Al Maruf, Post-Doctoral Fellow (Université Laval)
Suzanne Côté, Research Associate (Unité de recherche en santé publique)
Aurélie Maire, Research Associate (Centre de Recherche du Centre hospitalier de l'Université Laval)
Caroline Moisan, Research Associate (Centre de Recherche du Centre hospitalier de l'Université Laval)
Annie Turgeon, Research Associate (Centre de Recherche du Centre hospitalier de l'Université Laval)

ABSTRACT

Approximately 1000 Inuit living in the 14 communities of Nunavik participated in the health survey entitled ?Qanuippitaa? How are we?? during the fall of 2004. 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 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 the project's 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 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 is intended to provide stakeholders and authorities with solid ground on which to update policies and health programs in Nunavik, in particular to obtain the data required to support the next Strategic Regional Plan for health and social services.
- Themes to be addressed in the this participatory research are being defined together with Inuit co-researchers, representatives of the Nunavik Regional Board of Health and Social Services (NRBHSS) and in consultation with intersectoral organizations in Nunavik.
- The content of each theme is elaborated with experts from academia and refined through discussions with our Inuit co-leaders, NRBHSS representatives, clinicians in regional hospitals and members of key intersectoral organizations in Nunavik.
- Additional funding for *Qanuilirpitaa* is being requested from CIHR and other granting agencies.
- The Steering Committee of the health survey changed the name of the survey to *Qanuilirpitaa* – How are we now? - and postponed the field work to August-September 2017.

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 older than 30 years of age to ensure the representativeness of the adult cohort.

2. Youth component

Nesting this new youth cohort in *Qanuilirpitaa* 2017 will allow us: 1) To complement the adult follow-up by recruiting a new group of 1000 Nunavimmiut aged 16-30 year-old; 2) To study the evolution of the prevalence of risk factors and diseases in the 18-30 year-old population between 2004 and 2017; 3) To document new emerging threats to health and new indicators of health and well-being pertaining to the younger generation.

3. Community component

To identify, define and assess culturally appropriate community indicators of health and well-being. Specific objectives are: 1) To define community health and well-being from the perspective of Nunavimmiut; 2) To identify and describe elements that foster community health and well-being; 3) To develop indicators to assess, and ways to describe, community health and well-being.

INTRODUCTION

The health survey among the Inuit of Nunavik, entitled *Qanuippitaa* – How are we? - was conducted in all 14 Nunavik communities from August 27th to October 1st, 2004. The general aim of the survey was to gather social and health information on a set of themes including various health indicators, physical measurements, and social, environmental and living conditions, thus permitting a thorough update of the health and well-being profile of the Inuit population of Nunavik. The survey was also intended to provide stakeholders and authorities with solid ground on which to update policies and health programs in Nunavik. Twelve years later, there is a strong need to go back to the communities to document emerging issues arising in this small population in rapid transition, which is adopting a more sedentary lifestyle and new eating habits, while being confronted to a modified environment due to climate change.

A workshop entitled “Inuit Health in Transition Study: The Circumpolar Cohort Nunavik Planning Meeting”, convened by Nasivvik and other partners, took place June 11-13, 2012 in Kuujjuaq, Nunavik, to discuss the structure and priorities of future health studies in the region. Consultation meetings were also conducted with the Board of Directors and the Direction of Public Health of the NRBHSS. During this two-year consultation process, it was decided that the next Nunavik Health Survey will include three components/goals: 1) To follow-up the 2004 Nunavik adult cohort; 2) To conduct the first Nunavik Inuit Youth and Young Adult Health Survey; 3) To identify, define and assess culturally appropriate community indicators of health and well-being. Each component has specific scientific, technical and ethical issues to be addressed during the first 17-months of the grant period. Scientific groups were constituted to define those issues for each component (see “Activities” below). The first two components will include multiple markers of physical health (and diseases) as well as mental health and well-being, and will cover determinants of optimal health such as environmental contaminants, nutrition, substance use, sexual life, socioeconomic, psychosocial, family and community factors. The third component on community health and well-being is being developed with the aim of obtaining complementary quantitative and qualitative data at the community level in addition to the individual level. A **transversal theme on nutrition** was added because it is one of the most important determinants of health – not only with regard to its involvement in the etiology of chronic diseases – but also because it is a major target for public health interventions and/or community based-projects, which were mentioned during the 2012 workshop to be efficient in bringing positive changes in the communities.

ACTIVITIES

The governance structure of *Qanuilirpitaa* 2017 involves the participation of many members of the Nunavik communities, reflecting the participatory approach that characterizes this health survey. This structure is overseen by a *Steering Committee* composed of key regional leaders and representatives from Nunavik as well as the three main partners (NRBHSS/INSPQ/CHU de Québec Research Centre/Laval University). In order to ensure the overall guidance of the health survey, meetings of the *Steering Committee* were held throughout the year. The *Scientific Committee* reports to the *Steering Committee* on the scientific orientations of the survey. Meetings of the Scientific Committee took place periodically during the 1st year to oversee and support the development of the survey content, design and methodology. In addition to those committees, other committees were also created to support the project: the *Management Committee*, the *Logistic Committee* and the *Communication Committee*. These committees also held several meetings during Y1.

Adult and Youth components

- Throughout the year, both the *Adult component committee* and the *Youth component committee* held several meetings to define tools, questions, clinical tests and analyses that will be used to assess the different themes and to monitor the components' progress.
- Project staff were hired to provide support in the planning phase of the survey.
- Academic experts were consulted to discuss methodological aspects and provide the latest scientific advice in relation with their domain of expertise.
- Collaboration was established with two physicians practicing in Nunavik. A 1st meeting was organized to gather their comments and suggestions on the survey (December 15, 2015).
- Several consultations also took place in Nunavik: 1) Qanaaq meeting – Consultation with young Inuit in Inukjuaq (July 9 – 13, 2015); 2) SIPPE meeting – Consultation with the regional and Inuit experts on the theme of Family (September 15, 2015); 3) Presentation to KSB (Proposal for a youth training development partnership with KSB) – October 2, 2015); 4) Consultations with Nunavimmiut and Regional experts in Kangiqsualujjuaq and Kuujjuaq (December 1-4, 2015); 5) Consultation with Inuit experts in Kuujjuaq (January 20, 2016); and 6) Consultation with Regional experts in Kuujjuaq (January 22, 2015).

Community component

- Hiring staff to identify and review pertinent literature on concepts and tools to assess community well-being, community in health promotion and community conditions.
- Hiring of project staff in preparation for upcoming community consultations.
- A first meeting with mayors and employees from Landholding Corporations was conducted in Montreal (December 4, 2015).
- Work with language experts on health and wellbeing terminology.
- A PhD Student was recruited to document the use of social media in participatory research in Nunavik in relation to Qanuilirpitaa communications.

Nutrition theme

The 1st year objective of the Nutrition component was to evaluate data from previous studies and to determine the best tools for assessment of dietary intake and food InSecurity (FIS).

To achieve objectives related to nutrition component, we set up the Nutrition-Food InSecurity (N-FIS) Committee. This N-FIS Committee is composed of 16 members, including 10 nutritionists. Two meetings were organized in 2015 (October 6 and December 14). These meetings had two major topics. The first topic − the quantitative component of diet − aims to determine the tool and questions that we will use to assess dietary intakes in the more efficient and valid manner. The second topic − the Food In/Security (FIS) component − aims to determine the questions that we will use to assess efficiently FIS.

RESULTS AND DISCUSSION

Adult and Youth components

- A literature review was conducted to identify instruments that would be relevant to assess mental health related themes; we also inventoried questions, clinical tests and analyses used in main health surveys to assess physical health related themes.
- The following themes are ready to be presented to the *Steering Committee*: Social support, Victimization, Sexual health and Bullying.
- Instruments were identified for the following themes: Mental health and well being, Resilience, Self-esteem, Self-efficacy and Coping. The selection need to be done.
- Non-intentional accidents and trauma: selection of instruments is in progress.
- Selection of questions, analyses and clinical test needs to be conducted for the following themes: Cardiometabolic health, physical activity, gastroenteritis, zoonoses and waterborne diseases, *H. pylori,* hearing, oral health, respiratory health, neurotoxicity related to methylmercury exposure, kidney disease (related to diabetes), hepatotoxicity and nonalcoholic fatty liver disease (NAFLD), bone quality, musculo-skeletal diseases and cognitive decline.
- Justice and Elders' victimization: work will be initiated soon.
- Throughout the consultations, partnerships with local stakeholders were created and existing collaboration were strengthened.

Community component

So far, we have inventoried several conceptual models and instruments pertaining to: a) Community well-being, identifying concepts such as healthy community and healthy places, living conditions, social cohesion and social capital, community wellness, way of life, quality of life, vulnerability and resilience, caring for country, sustainable livelihoods, sustainability and vibrant communities; b) Concepts of community in health promotion: community capacity, empowerment, community readiness, community resilience, mobilisation, participation, sense of community, capacity building and community assets mapping; c) Tools for observation of community conditions: built environment (community design/land use, transportation), resources (availability, condition), safety and social and physical disorder.

The meeting with mayors allowed defining access to the land, and land-based activities, as an important component of community health and well-being. From these discussions, several possible indicators were formulated, based in part on indicators identified in the literature review and other health surveys in the Arctic.

The work with language experts on health and wellbeing terminology resulted in the ongoing development of a health and wellness lexicon that will serve to orient the questions and descriptions.

A protocol and methodology were developed for studying the use of social media in participatory research in Nunavik in relation to Qanuilirpitaa communications. A comprehensive survey of the literature was also produced on the subject (to be published in upcoming issue of Études Inuit Studies) and fieldwork in Puvirnituk will begin February 1, 2017.

Nutrition theme

First topic: quantitative component of diet

Based on work related to *N-FIS committee* meetings, the food frequency questionnaire (FFQ) has emerged as the preferred approach method to measure the long-term dietary intake. Classical methods based on interviews by dieticians (such as 24h-dietary recall) carry a heavy logistic burden and high costs. However, FFQs are easy for participants to complete, can be processed easily by computers, and are inexpensive. Moreover, FFQ visual and audio aids and pop-up windows could provide additional information to simplify responses, which is impossible with paper-and-pencil questionnaires.

The 2017-FFQ is almost completed. It includes follow-up questions of important diet components asked in the 2004 survey, but also includes follow-up of new dietary components.

Second topic: FIS component

Key components that were addressed on this topic are:

- The committee stated that the single FIS question asked in 2004 needs to be repeated for follow-up reason.
- Members of NNHC completed a questionnaire survey during the November meeting. Comparison with other measurements among Aboriginal populations was not the 1st priority identified by the NNHC members.
- However, the N-FIS committee advocates that we need some FIS questions to be able to make comparisons with other Aboriginal populations in Canada.
- The creation of an adapted tool for Inuit populations is the primary focus for all N-FIS and the NNHC members. In response to concerns about the validity of FIS measures in Nunavik, we are now conducting statistical analyses to examine the properties of the Household Food Insecurity and Access Scale (HFIAS) in a sample of pregnant women in Nunavik. These statistical analyses include the following methodologies: Rasch Rating Scale Model (RSM), Akaiki Information Criterion (AIC), Bayesian Information Criterion (BIC), Exploratory Factor Analysis (EFA), and Receiver Operating Characteristic (ROC) curves. The next step is to develop a modified version of HFIAS to improve its accuracy and efficiency.
- Another important issue that emerged from the December meeting is the importance to specify the type of food that we referring to in FIS questions. For some applicable questions, the new FIS questionnaire will ask specific questions pertaining to country or market foods.

Because the validity of dietary and FIS assessment methodologies is population and culture specific, sufficient validation of research tools is a particularly important step for studying dietary determinants of health and diseases. During Y2, the new FFQ and FIS questions will be validated and pre-tested.

CONCLUSION

We have made significant progress in designing the Qanuilipitaa 2017 health survey together with our Inuit co-leaders. We are confident that we will meet all of our objectives within the targeted timeframe and be ready for the field work in August-September 2017.

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Community Vulnerability, Resilience and Adaptation to Climate Change in the Canadian Arctic

Project Leader

James Ford (McGill University)

Network Investigators

Ashlee Cunsolo Willox (Cape Breton University)
Tristan Pearce (University of the Sunshine Coast)

Collaborators

Frank Duerden (Ryerson University)
William Gough (University of Toronto)
Sherilee Harper (University of Guelph)
Graham McDowell (McGill University)

HQP

Slawomir Kowal, Doctoral Student (University of Toronto)
Alexandra Sawatzsky, Doctoral Student (University of Guelph)
Lewis Archer, Masters Student (McGill University)
Dylan Clark, Masters Student (McGill University)
David Fawcett, Masters Student (University of Guelph - Department of Geography)
Linnaea Jasiuk, Masters Student (University of Guelph)
Knut Kitching, Masters Student (McGill University)
Genevieve Lalonde, Masters Student (University of Guelph - Department of Geography)
Eric Lede, Masters Student (Trent University)
Colleen Parker, Masters Student (University of Guelph - Department of Geography)
Anna Bunce, Technical Staff (McGill University)

Northern HQP

Mishak Allurut, Northern Research Staff (Qikiqtani Inuit Association)
Emily Kudlak, Northern Research Staff (Inuvialuit Cultural Resource Centre)
Roland Notaina, Northern Research Staff (Hamlet of Ulukhaktok)
Inez Shiwak, Northern Research Staff (Rigolet Digital Story Telling)
Jack Shiwak, Northern Research Staff (Nunatsiavut Government)
Michele Wood, Northern Research Staff (Nunatsiavut Government)

ABSTRACT

The Canadian Arctic is widely regarded as a global hotspot of climate change impacts. Implications will be particularly pronounced for Inuit, many of whom depend on hunting, fishing, and trapping; activities which continue to underpin livelihoods and economies, but which also create unique sensitivities to the rapidly changing climate. Communities will have to adapt to these changes and, in order to inform the development of adaptation strategies by households, communities, and governments, we need to know the nature and determinants of vulnerability and resilience to climate change. This research program seeks to expand our understanding of what makes communities vulnerable or resilient to the impacts of climate change. Focusing specifically on the Inuit harvesting sector, the program is underpinned by the development of a longitudinal community-based monitoring approach which will involve comparing the nature and determinants of vulnerability and resilience today with fieldwork conducted by team over a decade ago, and the creation of hunter monitoring teams to develop a real-time picture of how climatic conditions are experienced and responded to. With emphasis on real time monitoring, longitudinal analysis, and longterm collaboration, the findings of the work will help us examine and test conclusions reached by other studies, including our own, which we believe may not fully capture nature of vulnerability; unaddressed, we believe that policies based on existing knowledge could inadvertently be maladaptive. This novel approach will involve partnering with 3 Inuit communities from diverse areas of the Arctic (Ulukhaktok, NWT; Arctic Bay, NU; Rigolet, Nunatsiavut), and has an emphasis on creating science that can directly be used in decision making of our northern collaborators.

KEY MESSAGES

- Northern Canada has a long history of climate change vulnerability and resilience research, much supported through ArcticNet, but our understanding on the multi-scalar, dynamic nature of human-environment interactions in a changing climate is limited.
- This project builds on longstanding community partnerships to develop a longitudinal community-based monitoring approach for understanding and characterizing the dynamic nature of community vulnerability and resilience to climate change. The work focuses on wildlife harvesting & utilization, and land based dangers.
- Traditional ecological knowledge (TEK) is a key determinant of adaptation to changes affecting subsistence hunting. TEK underpins competency in subsistence and adaptations to changing conditions, which includes flexibility with regard to seasonal cycles of hunting and resource use, hazard avoidance through detailed knowledge of the environment and understanding of ecosystem processes, and emergency preparedness, knowing what supplies to take when traveling and how to respond in emergency situations.
- Activities in year 1 have primarily focused on conceptual and methodological development, reviewing the scholarship on vulnerability and resilience, discussing the state of the field with partners, advancing how we engage communities in human dimensions research, and establishing partnerships at the community level. The team has presented this work at major conferences, spent considerable time liaising with community partners, and published the work in major journals, including Nature.
- Year 1 has also seen significant progress in our restudy of community vulnerability and resilience in Arctic Bay, repeating an ArcticNet supported study done by the PI in 2004/05, using the same methodology, and asking the same people the same

questions. We plan to do the same in Ulukhaktok, NWT, and Rigolet, Nunatsiavut, in year 2. Two new communities have also been incorporated into the project to help us better understand the dynamic nature of community vulnerability and resilience.

- In year 2, the community based monitoring component of the project will be launched to help us document land use behavior in partner communities, and understand real-time how people respond to climate-related risks and opportunities. In year 1 we have been canvassing community input on this idea and examining how to make it feasible, sustainable, and effective.

OBJECTIVES

The overarching goal of this research program is to develop a dynamic understanding of the processes and conditions affecting community vulnerability and resilience to the effects of climate change. The research program is building on previous research by the team to develop and validate a longitudinal community-based monitoring approach. The project is working in the three communities specified in the original application: Ulukhakotk, NWT; Arctic Bay, NU; Rigolet, Nunatsiavut. In addition, two communities have been incorporated into the project: NI Dr. Pearce is leading work in Paulatuk, NWT, to better understand the role of multiple climatic and non-climatic stresses on human vulnerability to climate change and the dynamics by which communities respond to novel change, specifically examining how the community adapted to the arrival of beluga in the region in the 1970s and 80s, a trend now happening in Ulukhaktok; PI Dr. Ford is leading work in Arviat, NU, where his team first conducted vulnerability and adaptation research in 2010. The beluga work in Ulukhaktok is being jointly supported by ArcticNet project "Knowledge Co-Production for the Identification and Selection of Ecological, Social, and Economic Indicators for the Beaufort Sea" (Loseto), and the Arviat work by a Rotary Club grant ($60k, 2014-16). The overarching goal of the project will be achieved through 5 objectives:

Objective 1 – Conceptual development: This objective will develop and refine a conceptual approach for capturing the dynamic nature of vulnerability and resilience in Arctic communities. Part of this objective includes conducting a literature review of the impacts, adaptation, vulnerability, and resilience field in the Arctic.

Objective 2 – Methodological development: This objective will 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. This objective will build upon close collaboration with partner communities, and be directed by the principles of community-based and community-led participatory research (CBPR). This objective will be partly informed by a literature review on community based adaptation and vulnerability research.

Objective 3 – Empirical application: Data on vulnerability and resilience will be collected in partner communities, with the work focusing on two components of Inuit harvesting that have been identified as highly sensitive to climate change: wildlife management and utilization, and dangers of engaging in land based activities. Key activities include: i) A re-analysis on vulnerability and resilience in the three communities, comparing present day trends to previous work done by the team (Ford & Pearce); and ii) Establishing community based monitoring teams in partner communities to document land use real-time using GPS units, and interview land users on a regular basis on the harvesting activities and coping mechanisms.

Objective 4 – Adaptation planning: The research findings will inform adaptation planning by generating information on the dynamic nature of vulnerability, and working closely with decision makers to this end. This activity will also be informed by an evaluation of the current state of the adaptation landscape in the north.

Objective 5 – Examine broader insights of the work: This objective involves ongoing reflection by the team and partners to evaluate the findings within the context of other research on the human dimensions of arctic change. Broader-level understanding of the dynamic nature of vulnerability and resilience will be derived from comparing the findings to past vulnerability research in these and other locations.

We have made significant progress on objectives 1 and 2, and empirical work for the longitudinal assessment is advanced in Arctic Bay, Ulukhaktok, and Arviat. With regards to community based monitoring, the first year has focused on soliciting community feedback on the proposed work and establishing protocols and monitoring teams. In both Ulukhaktok and Rigolet we hope to soon rollout the monitoring component of the project.

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 particular sensitivities to the rapidly changing climate. Inuit will have 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 also the capacity to adapt? This requires working with people in communities to identify what climatic stresses are relevant and important to them 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, however, 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 and utilization, land dangers), and are constraining our ability to identify and examine potential future vulnerabilities and identify sustainable and effective adaptations.

This deficit in understanding stems from conceptual and methodological limitations of current work, which have typically utilized a retrospective study design where an understanding of the factors affecting vulnerability and resilience is derived from an assessment of how climatic conditions currently affect the subsistence sector and have done so in the past. This has generated a wealth of information on the determinants of vulnerability, but the retrospective nature of data collection presents challenges: interviewees often only recount what they have recently experienced, the season during which research takes place influences what is recounted, and details about the nature of risks and coping strategies recedes as time passes. This creates difficulties for understanding the role played by multiple stresses in affecting vulnerability and resilience, identifying the place-specific nature of risks, situating current experience in a broader historical context, and accounting for the evolution of vulnerability over time.

New approaches and methodologies are needed if we are to create a more dynamic understanding of vulnerability, the development and application of which underpin this ArcticNet project.

ACTIVITIES

In this section we outline key activities undertaken in year 1, organizing by specific objectives. We note herein that the project is jointly funded by a SSHRC Insight Grant ($500k, 2014-2019).

Objective 1 - Conceptual development

Year 1 has had a major focus on developing the conceptual approach of the project, and has built upon specific activities including: a workshop at McGill on community based adaptation attended by the PI, NIs, and students, with an article in press at *WIREs Climate Change* a key output; a literature review and critical examination of Arctic-focused vulnerability and resilience scholarship framed around the question, what are the challenges to adaptation in the Arctic?, and recently published in *Nature*; the publication of a conceptual and reflective paper in *Arctic* on the role of Inuit traditional knowledge in climate adaptation and how it can best be integrated into research; an examination of how to best incorporate gender considerations into human dimensions of Arctic change research, recently published in *Env Research Letters*; and, interviews with practitioners and decision makers in the North on how vulnerability and adaptation assessments can be enhanced. Based on these activities, and also informed by the work of MA students Lewis Archer and Dylan Clark (McGill), a first generation conceptual model has been developed, focusing the dynamic interrelationship between human and biophysical factors that create vulnerability or enhance resilience. This model is guiding the MA work of both students, and will be further advanced by work planned in 2016 by the PI and NI Tristan Pearce. Further community consultations and decision maker feedback are also scheduled for 2016.

Output

Peer Reviewed Articles

- Ford, J., McDowell, G., Pearce, T. (2015). The adaptation challenge in the Arctic. Nature Climate Change, 5, 1046-1053.
- Pearce, T., Ford, J., Cunsolo Willox, A., and Smit, B. (2015). Inuit Traditional Ecological Knowledge in Adaptation to Climate Change in the Canadian Arctic. Arctic, 68(2), 233-245.
- Ford, J. et al. (2015). Community based adaptation research in the Canadian Arctic. WIRES Climate Change.

- Bunce, A., and Ford, J. (2015). How is adaptation, resilience, and vulnerability research engaging with gender? Environmental Research Letters.

Presentations

- Ford, J., McDowell, G., and Pearce, T. (2015). The adaptation challenge in the Arctic. Our Common Future, Paris, July 2015.
- Fawcett, D., Pearce, T. and Ford, J. (2015). A longitudinal approach to assessing vulnerability to climate change in Ulukhaktok, NWT, Canada. Poster presented to the ArcticNet Annual Scientific Meeting, Vancouver, Canada, 7-11 December 2015.
- Cunsolo Willox, A., Bunce, A., Sawatzky, A., Shiwak, I., Shiwak, J., Ford, J., Furgal, C., Edge, V., and Harper, S. (December 2015). Building Local and Indigenous Knowledge Systems (Building LINKS): Community-Led Environment and Health Surveillance for Adaptation. Adaptation Conference, Ottawa, Ontario, April 2016.
- Sawatzky, A., Cunsolo Willox, A., Harper, S., Shiwak, I., Wood, M., the IMHACC Team, and the Rigolet Inuit Community Government. (2015). Exploring Pathways for Wellbeing Among Labrador Inuit. Graduate Research Seminar Series, Ontario Veterinary College, University of Guelph, Guelph, Ontario, Canada, November 18, 2015.
- Cunsolo Willox, A., Harper S., Shiwak, I., Shiwak, J., Wood, M., and the Rigolet Inuit Community Government. (2015). Introducing the Building-LINKS project. Research Symposium, October 2015, Goose Bay, Labrador.

Outreach

Ulukhaktok, NT

- **Meeting with Ulukhaktok Community Corporation (UCC):** researchers met with the UCC to discuss the research project, identify opportunities for local involvement and possible collaboration with other climate change related projects, in particular the Inuvialuit Regional Corporation's climate change and youth initiative.

Rigolet, Nunatsiavut

- **Community Open House**: During a trip to Rigolet in Fall 2015, the project team held a Community Open House, with two opportunities for attending: an afternoon and an evening session. These events shared project ideas and getting extensive feedback on strategies for community-based monitoring approaches and how to track and measure adaptive capacities. This event was attended by over 60 community members
- **Community Stakeholder Meetings:** During the same trip above, the project team met with key stakeholder groups – health professionals, Town Council, Northern Rangers, and Wildlife specialists – to discuss strategies for community-based monitoring approaches, tracking and measuring adaptive capacities over time, and usability of research results and outputs.
- **Key Stakeholder and Government meeting**: This event was held in Happy Valley-Goose Bay, Labrador, and brought together government representatives, municipal leaders, wildlife specialists, health professionals, and key stakeholders to discuss the project and provide valuable input into community-based monitoring and long-term tracking, measuring, and evaluating adaptive capacities.
- **Key Stakeholder Interviews:** Conducted in July and August in Goose Bay, Labrador, a project assistant interviewed 17 key stakeholders from health, government, wildlife, and culture sectors to gather in-depth interviews about long-term land-use monitoring, longitudinal studies of climate change, and adaptive capacities among Nunatsiavut Inuit.
- **Community Interviews:** In October 2015, one of the project graduate students interviewed 15

community members in Rigolet to gain in-depth understanding of community needs around adaptation planning, community monitoring needs, participatory app development, and overall changes in climate, weather, environment, wildlife, and plants in the past 5-10 years.

- **Reverse Trick-or-Treating:** On Halloween, members of the research team went door-to-door in Rigolet, handing out small packages of candy, information about the project, and a thank you note from the team for participating. All households in Rigolet were visited.
- **Land Trip:** While in Rigolet in the Fall, members of the team did some preliminary land trips to get a sense of what people wanted monitored, how, and what technologies or strategies could be utilized.

Objective 2 – Methodological development

Two activities underpin the empirical work that will be undertaken as part of the project. Firstly, the team will replicate vulnerability assessments conducted while they were ArcticNet supported graduate students in the case study communities, using a consistent approach and methodology, and interviewing the same community members and relevant decision makers. For Arctic Bay and Ulukhaktok it will be a decade since the original research was conducted, in Rigolet five years. The aim of the longitudinal restudy of this nature is us to examine how continuing and rapid socio-ecological transformations have affected human-environment interaction; test hypotheses on vulnerability and resilience determinants developed during our graduate and follow-up work; and begin to examine the dynamics of vulnerability (to be substantiated by real-time monitoring). Data will be collected and analyzed consistent with previously published research, using semi-structured interviews, focus groups, and participant observation as the main means of data collection tools. This will be supported by repeat visits made the research team on a regular basis and at different times of the year to allow us to observe climatic-related risks affecting harvesting, document real-time coping mechanisms, and observe changes in human-environment interactions.

The second component of the methodological objective is to employ local people in the partner communities to collect land use and harvesting data on a regular and ongoing basis (i.e. community based monitoring (CBM)). Combined with the restudies, CBM can help unravel the complex interaction and evolution of vulnerability and resilience over time in a specific location.

Outputs

Presentations

- Pearce, T. and Ford, J. (2015). Current directions for climate change vulnerability and adaptation research. Paper presented to ArcticNet Annual Scientific Meeting, Vancouver, Canada, 7-11 December 2015.
- Lede, E. (2015). Dynamic vulnerability and the role of multiple stressors in adaptation to climate change in the Arctic. Sustainability Research Centre invited presentation, University of the Sunshine Coast, Queensland, Australia, 17 November 2015.
- Cunsolo Willox, A., Harper S., Shiwak, I., Shiwak, J., Wood, M., and the Rigolet Inuit Community Government. (2015). Introducing the Building-LINKS project. Research Symposium, October 2015, Goose Bay, Labrador.

Objective 3 – Empirical application

The conceptual approach and methodology are being applied in the three communities specified in the application. Arviat and Paulatuk have also been incorporated into the project to provide additional insights, and reflects opportunities to work in these communities that have arisen since the application to ArcticNet was made. On the basis of community consultation and established need, the research is focusing on vulnerability and resilience within two components of Inuit harvesting that have been identified as highly sensitive to climate change: wildlife management & utilization, and the dangers of engaging in land based activities.

The Arctic Bay restudy is nearing completion, with the work conducted by MA student Lewis Archer (McGill) based on >40 semi-structured interviews with community members, and analysis of climate and sea-ice data over the last 40 years (from NI Dr. Gough's team). Archer will have finished his MA by spring, and we are exploring the option of having a recently recruited PhD student (Galapatthi, McGill) examine in greater depth findings around social learning. The Ulukhaktok restudy will be undertaken by MA student David Fawcett (Guelph / USC), with fieldwork planned for 2016; NI Pearce has already established the community team to help David in his work, and Dr. Gough's team have analyzed sea ice and climate data for the community. The Rigolet restudy is currently in planning.

The newly developed foci in Arviat has a specific focus on land dangers and the evolution of danger over time, and is being led by MA student Dylan Clark. He has made repeat visits to the community in 2015, interviewed ~ 15 community members and engaged in participation observation through extensive engagement in land based activities. Clark's work has also developed a quantitative approach for examining the drivers of search and rescue (S&R) in northern communities, which has been applied to Nunavut S&R data, and is helping inform the qualitative work that is seeking to understand drivers of vulnerability to land dangers. Data for the Paulatuk case study will be collected by MA student Eric Lede between January and March 2016.

An initial focus in Ulukhaktok was to examine an Inuit identified determinant of adaptation in the subsistence hunting sector, traditional ecological knowledge (TEK) and a barrier to the transmission of TEK, formal schooling. MA student Genevieve Lalonde (Guelph, Dr. Pearce) conducted 35 interviews with Inuit in Ulukhaktok to identify what aspects of culture and modes of learning they deemed important for younger generation Inuit to learn and opportunities to include this within the formal school system.

We are currently in the process of establishing hunting and key informant teams in Ulukhaktok and Rigolet, and developing data collection protocols. The Rigolet portion of the work is leveraging three-year funding from POLAR Knowledge Canada to develop a participatory land-use mapping and monitoring app, that is Inuit-designed and includes Inuit-specific indicators and measurements. Successful piloting in these communities, combined with the need for additional funds, will determine if the CBM will be rolled out in the other communities.

Peer Reviewed Articles

- Clark, D., Ford, J., Berrang-Ford, L., Pearce, T. et al. (in review). The role of environmental factors in search and rescue incidents in Nunavut. Canadian Medical Association Journal.
- Lalonde, G., Pearce, T. and Dickson, J. (in review). Perceptions of learning success among Inuit and southern educators in Ulukhaktok, NT. Canadian Journal of Education.

Presentations

- Lalonde, G. and Pearce T. (2015). Inuit culture and education in Ulukhaktok, NT. Poster presented to the ArcticNet Annual Scientific Meeting, Vancouver, Canada, 7-11 December 2015.
- Lede, E., Pearce, T. and Furgal, C. (2015). The influence of multiple stressors on vulnerability and adaptation to climate change in Paulatuk, NT. Poster presented to ArcticNet Annual Scientific Meeting, Vancouver, Canada, 7-11 December 2015.
- Cunsolo Willox, A., Harper S., Shiwak, I., Shiwak, J., Wood, M., and the Rigolet Inuit Community Government. (2015). Introducing the Building-LINKS project. Research Symposium, October 2015, Goose Bay, Labrador.
- Clark, D., Ford, J., Berrang-Ford, L., Pearce, T., Gough, W., Kowal, S. (2015) Environmental

Dimensions of Search and Rescue and Injury in Nunavut. ArcticNet, December 2015, Vancouver.

Outreach

- Clark, D. (2015) Climate Change Dimensions in the Arctic. Rotary International, August 2015, Colorado, USA.
- Clark, D. (2015) Search and Rescue in Nunavut. Rotary International, October 2015, Montreal.
- Collaboration with key stakeholders in Arviat to disseminate research results and produce actionable guidelines. Dylan Clark has been, and continues to work with the Arviat Young Hunters program, Arviat Film Society, Arctic College – Arviat, and Isuma TV. Land safety risks and safety practices observed in Dylan's MA work will be incorporated into youth land trips and a film in 2016.

Objective 4 – Adaptation planning

The research findings will inform adaptation planning by generating information on the dynamic nature of vulnerability. To achieve this, we first need to understand what information is needed, what adaptation programs and policies have already been supported, and what adaptation needs are. To this end, and supported by co-funding from SSHRC, in year 1 we have focused on evaluating the current adaptation landscape in Nunavut, using publically available information and interviews with northern decision makers, scientists, and stakeholders (n=50). This work has been led by McGill full-time RA Jolene Labbe and MA student Melanie Flynn. Three publications from this work will be submitted in 2016. We have also examined adaptation planning initiatives in the NWT.

Adaptation planning initiatives in the NWT were focused on strategies currently in use, and those desired to include Inuit Culture in education. This research necessitated working with local and territorial partners in order to fully understand the education and learning paradigm at various scales. Communications with the NWT education renewal and innovation, the Beaufort Delta Education District and the local District Education Authority were essential. Continuous communication examined projects and initiatives being conducted at the community level and their influence on adaptation strategies at the local scale (N=30). Results from this research will be used by the various scales of governance, particularly the NWT Education Renewal and Innovation framework working to include more aspects of Inuit culture in the formal education system. This work has been led by MA candidate Geneviève Lalonde, two publications are anticipated in 2016.

Presentations

- Labbé, J., Flynn, M., Ford, JD. (2015). Adaptation readiness and the big picture in Nunavut: an evaluation of the current state of adaptation, its key linkages and barriers. ArcticNet, December 9, 2015, Vancouver, BC.
- Labbé, J., Ford, JD., Flynn, M., Araos Egan, M. (2015). Adaptation to climate change in Nunavut: Where are we at and where do we go from here. Poster presentation ArcticNet, December 8-9, 2015, Vancouver, BC.
- Labbé, J., Ford, JD, Flynn, M., Araos Egan, M. (abstract under review). Adaptation to climate change in Nunavut: Where are we at and where do we go from here? Adaptation Futures, May 10-13, 2016, Rotterdam.
- Labbé, J., Ford, JD. (2016 invited presentor). Adaptation to Climate Change Tracking in Nunavut. Regards multidisciplinaires sur l'adaptation aux changements climatiques, May, 2016. UQAM, Montréal, QC.
- Labbé, J., Flynn, M., Ford, JD. (abstract under review). Adaptation readiness and the big picture in Nunavut: an evaluation of the current state of adaptation, its key linkages and barriers. Adaptation Futures, May 10-13, 2016, Rotterdam.
- Ford, JD., Labbé, J. Flynn, M., Araos Egan, M., Lesnikowski, A., Austin, SE, and OURANOS.

(panel session under review). Adaptation Tracking panel. Adaptation Canada 2016, Ottawa, ON.

- Labbé, J., Ford JD, Flynn, M., Araos Egan, M. (abstract under review) Adaptation to climate change in Nunavut: Where are we at and where do we go from here? Adaptation Canada 2016, Ottawa, ON.

Outreach

- Labbé, J. (2015). Adaptation to climate change in Nunavut: Where are we at and where do we go from here? Invited presentation for GEOG 200: Geographical Perspectives on World Environmental Problems, McGill University, Qc, Canada, October, 8, 2015.
- Labbé, J., Flynn, M. (2015). Adaptation in Nunavut. Invited Presentation by OURANOS, April 2015, Montréal, QC.
- Labbé, J., Flynn, M., and Ford JD organised meeting with OURANOS Northern project team members to present preliminary results of the Adaptation in Nunavut project and discuss potential avenues for future collaboration. September 21, 2015, Montréal, QC.
- Collaboration and preliminary results sharing and discussion on Adaptation in Nunavut project key stakeholders meetings over the course of the last year throughout all stages of the project and again at ArcticNet 2015 conference in Vancouver. Stakeholder feedback on project design and methods from December 2014 onward. At the conference, Jolène Labbé discussed preliminary results and planning for dissemination in the new year with key stakeholders and end-users side meetings. Dissemination options include: co-authored publications, presentations to key stakeholders and project participants in Iqaluit and Ottawa, summary report or booklet for decision-makers in government and adaptation database sharing avenues.

Objective 5 – Examine broader insights of the work

This will be the focus of year 3.

Activities spanning objectives

- Cross-university partnerships were established between the universities of the PIs. For example, Dr. Pearce serves on the committee of two McGill students, Dr. Ford is on the committee on one Guelph student (Fawcett) and one USC student (Lede), Dr. Cunsolo Willox is jointly supervising a full-time RA based at McGill, and MA student Dylan Clark spent time in Dr. Gough's lab at UoT. Co-authored journal articles and co-organized special sessions at conferences have further strengthened ties and networking among the team.
- Multiple presentations and posters were given by project PIs and students at the annual science meeting in Vancouver. Anna Bunce, McGill, won 1st place in the health and social sciences category of the student poster contest.
- The project was presented at booth at the UN COP21 climate change meeting in Paris, 30th November-5th December, 2015.

Other

- PI Dr. Ford continued to represent the health and social science of the ArcticNet RMC
- PI Dr. Ford is a lead author for the northern chapter of NRCan's national assessment of climate change and the coasts, and the synthesis chapter of the AACA assessment.

RESULTS

Ford, McDowell, Pearce. (2015). The adaptation challenge in the Arctic. Nature Climate Change, 5, 1046-1053.

It is commonly asserted that human societies in the Arctic are highly vulnerable to climate change, with the magnitude of projected impacts limiting the ability to adapt. At the same time, an increasing number of field studies demonstrate significant adaptive capacity. Given this paradox, we review climate change adaptation, resilience, and vulnerability research to identify and characterize the nature and magnitude of the adaptation challenge facing the Arctic. We find that the challenge of adaptation in the Arctic is formidable, yet suggest that drivers of vulnerability and barriers to adaptation can be overcome, avoided, or reduced by individual and collective efforts across scales for many, if not all, climate change risks.

Pearce, Ford, Cunsolo Willox, and Smit (2015). Inuit Traditional Ecological Knowledge in Adaptation to Climate Change in the Canadian Arctic. Arctic, 68(2), 233-245.

This paper examines the role of Inuit traditional ecological knowledge (TEK) in adaptation to climate change in the Canadian Arctic. It focuses on Inuit relationships with the Arctic environment, including hunting knowledge and land skills, and examines their roles in adaptation to biophysical changes that affect subsistence hunting. In several instances, TEK underpins competency in subsistence and adaptations to changing conditions, which includes flexibility with regard to seasonal cycles of hunting and resource use, hazard avoidance through detailed knowledge of the environment and understanding of ecosystem processes, and emergency preparedness, e.g., knowing what supplies to take when traveling and how to respond in emergency situations. Despite the documented importance of TEK in adaptation and in maintaining a level of competency in subsistence, the relationships between TEK and adaptation to climate change are not well defined in the scholarly literature. This paper aims to conceptualize the relationships between TEK and adaptation to climate change by drawing on case study research with Inuit in the Canadian Arctic. TEK is considered an element of adaptive capacity (or resilience) that is expressed as adaptation if TEK is drawn upon to adapt to changing conditions. This capacity depends on the development, accumulation, and transmission of TEK within and among generations.

Ford et al. (2015). Community based adaptation research in the Canadian Arctic. WIRES Climate Change.

Community-based adaptation (CBA) has emerged over the last decade as an approach to empowering communities to plan for and cope with the impacts of climate change. While such approaches have been widely advocated, few have critically examined the tensions and challenges that CBA brings. Responding to this gap, this article critically examines the use of CBA approaches with Inuit communities in Canada. We suggest that CBA holds significant promise to make adaptation research more democratic and responsive to local needs, providing a basis for developing locally appropriate adaptations based on local/indigenous and Western knowledge. Yet, we argue that CBA is not a panacea, and its common portrayal as such obscures its limitations, nuances, and challenges. Indeed, if uncritically adopted, CBA can potentially lead to maladaptation, may be inappropriate in some instances, can legitimize outside intervention and control, and may further marginalize communities. We identify responsibilities for researchers engaging in CBA work to manage these challenges, emphasizing the centrality of how knowledge is generated, the need for project flexibility and openness to change, and the importance of ensuring partnerships between researchers and communities are transparent. Researchers also need to be realistic about what CBA can achieve, and should not assume that research has a positive role to play in community adaptation just because it utilizes participatory approaches.

Clark, Ford, Berrang-Ford, Pearce, Gough, Kowak. (In review). The role of environmental factors in search and rescue incidents in Nunavut. Canadian Medical Association Journal.

Unintentional injury is a leading cause of morbidity and mortality in Nunavut, where the importance of land-based activities and reliance on semi-permanent trails creates unique risk profiles. Climate change is believed to be exacerbating these risks, although no studies have quantitatively examined links between environmental conditions and injury and distress in the Canadian Arctic. We examine the correlation between environmental conditions and land-based search and rescue (S&R) incidents across Nunavut, comparing weather and ice conditions during 202 S&R incidents to conditions during 755 non-S&R days (controls) between 2013 and 2014. We show daily ambient temperature, ice concentration, ice thickness, and variation in types of ice to be correlated with S&R rates across the territory during the study period. These conditions are projected to be affected by future climate change, which could increase demand for S&R and increased injury rates in absence of targeted efforts aimed at prevention and treatment. This study provides health practitioners and public health communities with clearer understanding to prepare, respond to, and prevent injuries across the Arctic.

DISCUSSION

Research examining vulnerability and resilience is central to human dimensions of climate change scholarship, and plays a critical role in revealing where, how, and why people are affected by changes in the climate system. The importance of such work is now widely recognized, with observed and projected climatic changes adding urgency to the need for understanding the implications of a rapidly changing climate. To this end, community-level assessments have proliferated over the last twenty-five years, contributing to a growing body of evidence about the pathways through which climate change affects human systems. A number of keystone papers theorizing how to best study vulnerability and resilience were published in the early to mid-2000s, but since these seminal papers few projects have sought to advance the field conceptually, methodologically, or empirically. Our understanding of vulnerability and resilience in many cases is limited, with few studies incorporating longitudinal analyses or real time monitoring to understand how communities experience and respond to climate change in the context of multiple socio-economic-cultural changes.

Arctic research has been at the forefront of vulnerability and resilience research, but many of the challenges facing the general scholarship are also evident in northern work; the majority of studies, for example, are based on short term data collection and lack a fail to capture the dynamics of how communities experience and respond to change. Social learning, thresholds of response, feedbacks, and complex behavior are all theorized to be important in how social ecological systems respond to change, but Arctic work has generated only minimal insights on them. This projects seeks to address this deficit, with a focus on how community vulnerability and resilience evolve over time, combining insights from restudies in partner communities and real-time monitoring of human-environment behavior. The project is in its infancy with the majority of work and associated publications focusing on conceptual and methodological development.

Results are in their early stages, with emerging findings from Arctic Bay indicating significant short term adaptive capacity underpinned by social learning and experimentation in the face of rapid change, but with concerns that short term coping mechanisms may be maladaptive in the long term through overspecialization, downstream effects, and knowledge loss. In Ulukhaktok meanwhile, the opportunistic harvesting of beluga, a species historically not found in the region, indicates the adaptive capacity of harvest system to take advantage of new opportunities. Yet concerns emerged around the skillsets required to harvest beluga safely and sustainably, and need for hunting equipment not possesed by all, raising interesting questions around longer term social learning if beluga continue to migrate into the region. The importance of socio-economic drivers of vulnerability and resilience is evident in our analyses of search and rescue (S&R) data in Nunavut, which show that while sea ice conditions are correlated with land emergencies, the biggest driver is mechanical and closely linked to snowmobile maintenance and mechanical competence.

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Conclusion and References sections were missing from this report.

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Foodborne and Waterborne Disease Mitigation: Community-based Surveillance for Environmental Health

Project Leader

Sherilee Harper (University of Guelph)

Network Investigator

Jan Sargeant (University of Guelph)

Collaborators

Maureen Baikie (Department of Health and Social Services (Iqaluit))
Lea Berrang-Ford (McGill University)
Ashlee Cunsolo Willox (Cape Breton University)
Victoria Edge (University of Guelph)
James Ford (McGill University)
Jamal Shirley (Nunavut Research Institute)
Inez Shiwak (Rigolet Digital Story Telling)
Jack Shiwak (Nunatsiavut Government)
Scott Weese (University of Guelph)
Michele Wood (Nunatsiavut Government)

HQP

Danielle Julien, Doctoral Student (University of Guelph)
Lindsay Day, Masters Student (University of Guelph)
Anna Manore, Masters Student (University of Guelph)
Stephanie Masina, Masters Student (University of Guelph)
Ellen McDonald, Masters Student (University of Guelph)
Anna Bunce, Technical Staff (McGill University)
Rebecca Palmer, Undergraduate Student (University of Guelph)

ABSTRACT

Recent research uncovered the highest rates of self-reported enteric illness (i.e., diarrhea and vomiting) reported in the world to be in Iqaluit, Nunavut, and Rigolet, Nunatsiavut. Infectious diarrhea and vomiting can be caused by contaminated drinking water (i.e., waterborne disease), contaminated food (i.e., foodborne disease), or person-toperson contact. To reduce the high rates of diarrhea and vomiting in Northern Canada, we must monitor these pathogens causing illness to understand what pathogens are responsible for illness and how people contract the illness. The goal of this project is to create a participatory, community-based monitoring system to collect information on food and water contamination, and whether or not food and water contamination is causing illness in people in Iqaluit and Rigolet, Canada. This information will be important to understand why rates of diarrhea and vomiting in these communities appear to be high. The research team will work with Northern partners to use the research results to develop potential public health response options to reduce the high rate of illness. Training is an important focus of the project. Graduate students will learn community-based approaches to research through hands-on experience with partner organizations and community members. Inuit researchers will be trained in sampling and testing food and water for pathogens that can cause food- and waterborne disease. Northern collaborators will contribute to all phases of the research design, data collection, analysis, interpretation, and results dissemination process.

KEY MESSAGES

- Foodborne and waterborne disease is a global public health priority,[1] exacerbated by climate change, shifting populations 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: enteric illness incidence in these communities was 3x higher than national averages, and the highest in the global literature.[7]
- The end-user identified solution to the high rate of enteric illness in the North was a community-based surveillance system. As such, our project aims to create a participatory, community-based surveillance system to understand, respond to, and reduce the burden of foodborne, waterborne, and zoonotic enteric pathogens in Northern locales.
- We are slightly ahead of the schedule outlined in our proposal. In Year 1, we completed Phase 1 (finalized our surveillance concept, methodologies, and methods), and we have began Phase 2 (data collection and empirical research). In Year 1, we:
  - Trained three Inuit and four graduate students
  - Presented 10 presentations at conferences
  - One published manuscript, and three manuscripts prepared for peer-review
  - Highlighted the project in two media interviews
  - Secured $175,800 in matching non-NCE partner funds; this is approximately twice the funds provided by ArcticNet. Additional funds were secured from CIHR. In Year 2, we anticipate that we will be able to leverage three times the funds provided by ArcticNet.

OBJECTIVES

Our project aims to create a participatory, community-based surveillance system to understand, respond to, and reduce the burden of foodborne and waterborne enteric pathogens in Iqaluit.

In Year 1, we began to pursue the objectives outlined in our proposal:

1. **Establish a transdisciplinary team:** We have assembled a team of transdisciplinary scholars, government representatives, and Inuit community members, with expertise in the medical, veterinary, environmental science, public health, and social science fields. This team prepared the proposal, developed the study design, and will continue to work together as partners through each stage of research. We anticipate that this team will continue to expand and grow over the course of the project.
2. **Characterize water and food systems:** Understanding and respecting the social, cultural, and environmental constructs and pathways through which foodborne, waterborne, and zoonotic enteric pathogens could be transmitted is key to developing a surveillance system that respects and reflects Inuit culture, and provides the necessary information to identify and control disease. We have made great progress in examining the relationship Inuit have with food, water, and pets in the context of foodborne, waterborne, and zoonotic enteric disease.
3. **Pathogen source attribution:** To understand foodborne and waterborne disease transmission, this program will estimate the prevalence, identify risk factors, and examine molecular source attribution enteric pathogens in food (retail and country food), water (tap and brook water), and animals (domestic dogs, working dogs). This year, Northern partners have identified the pathogens that will be examined, decided what types of samples that will be tested (e.g. which food sources, etc), and co-developed data collection protocols that maximize Northern research capacity development and training.
4. **Effective knowledge translation and extension (KTE):** On-going and meaningful collaboration with Inuit stakeholders, health professionals, and Inuit organizations is essential to develop and evaluate a culturally acceptable and effective knowledge translation program to reduce foodborne, waterborne, and zoonotic enteric illness. Our end-users believe that the information that will be gleaned from this study will be critical to develop new or enhance existing public health planning, programming, and policy to effectively reduce the high reported burden of enteric illness. This year we have focused on establishing a strong foundation for an "integrated KTE" approach, whereby KTE is integrated throughout the program, and not only at the end of the program.

INTRODUCTION

Foodborne and waterborne disease is a global public health priority,[1] exacerbated by climate change, shifting populations 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.[8–14,7] 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.

The highest reported incidence of enteric illness in the world is in Northern Canada: Indigenous populations often live in substandard conditions and have more limited access to services and resources than 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.

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 been studied in these communities.

The end-user identified solution to the problem is a community-based surveillance system: Through proof-of-concept work, the research team and end-users identified a community-based surveillance system as an essential component for understanding, and thus reducing the high burden of enteric illness in Northern Canada. The end-users believe that a participatory, community-based surveillance system will enable a baseline understanding, enhanced response, and ultimately reduced foodborne and waterborne enteric pathogens. Importantly, the surveillance program is not the product of this research; rather, the desired outcome is to use surveillance as a tool to detect endemic and outbreak cases of illness, and understand the epidemiology of enteric illness in the North to develop response protocols; all of which are intended to reduce the burden of illness.

ACTIVITIES

Overview of Project Phases:

- **Phase 1) Conceptual and Methodological Development:** Develop a participatory, community-based surveillance system to monitor and respond to food- and waterborne infections in Northern Canada. (Year 1; completed)
- **Phase 2) Data Collection and Empirical Research:** Collect and analyze surveillance data. (Year 2-3)
- **Phase 3) Comparative Analysis:** Examine similarities and differences between communities and other locales. (Year 3)
- **Phase 4) Knowledge Translation and Exchange (KTE):** Develop locally-appropriate and culturally-relevant knowledge translation techniques. (Years 1-3)

Focus of Year 1:

In Year 1, we completed our planned activities, milestones, and project deliverables, which primarily focused on Conceptual and Methodological Development (Phase 1 completed), as outlined in our proposal. As we near the end of Year 1, we are transitioning our focus to Data Collection and Empirical Research (Phase 2).

Phase 1 Completed: Finalized Surveillance Concept, Methodologies, and Methods

- ***Phase 1 Summary:*** We worked with local partners to develop a monitoring system to capture data on enteric pathogens in humans, animals, food, and water. As outlined in the proposal, collaboratively developing the concept, methodologies, and methods of the surveillance system was the focus of Year 1.
- ***Responding to ArcticNet's Recommendations:*** We modified our project to reflect to the new budget and recommendations made by ArcticNet's Proposal Review Committee. The changes requested by the committee included:
  - » ArcticNet Recommendation #1: Partnering with Iqaluit and not Rigolet: Our Rigolet partners were disappointed by this recommendation; however, we are currently seeking additional funds to expand the work to Nunatsiavut. This change meant that HQP Bishop and Wright, who were working in Rigolet, are no longer part of the ArcticNet work. Rigolet partners are still engaged in the ArcticNet work, as they are interested in establishing similar projects in Nunatsiavut.
  - » ArcticNet Recommendation #2: Halving the budget and seeking additional funding: Our budget cuts were offset by only working with one community (instead of two communities) and securing additional matching funds.
  - » ArcticNet Recommendation #3: Partnering with Drs. Goldfarb and Yansouni: Drs. Goldfarb and Yansouni will test children's stools for enteric pathogens and we will test environmental exposures. By combining our work, we will provide a systems perspective of enteric illness in Iqaluit.
  - » ArcticNet Recommendation #4: Reduce the Knowledge Translation Budget: We cut the annual workshop in Ottawa to reduce this budget line.
- ***Meetings with Federal Stakeholders:*** We arranged several in-person meetings (n = 6 meetings) with various federal stakeholders (n = 15 people) to expand our research partnerships, co-develop the surveillance concept and methods, and increase matching funds. We met with representatives from:
  - » Centre for Foodborne, Environmental and Zoonotic Infectious Diseases, Public Health Agency of Canada
  - » FoodNet Canada, Public Health Agency of Canada
  - » Laboratory for Foodborne Zoonoses, Public Health Agency of Canada
  - » Strategic Policy, Planning and International Affairs Branch, Public Health Agency of Canada
  - » Indigenous and Northern Affairs Canada
- ***Meetings with Northern Stakeholders:*** We arranged several in-person meetings (n = 14 meetings) with various Northern stakeholders (n = 20 people) to expand our research partnerships, co-develop the surveillance concept and methods, and increase matching funds. To promote meaningful and strong Northern engagement in research design, we met with each stakeholder three times (August, October, and February), including representatives from:
  - » Nunavut Research Institute
  - » Department of Health, Government of Nunavut
  - » Nunavut Climate Change Centre
  - » Qaujigiartiit Health Research Centre
  - » City of Iqaluit

   - » Iqaluit Public Health
   - » Nunavut Tunngavik Inc.

- ***Meetings with Northern Healthcare Professionals:*** We arranged several meetings with healthcare providers in Iqaluit, including physicians, primary health nurses, public health nurses, and support staff.
- ***Priority Setting Meeting:*** In collaboration with Drs. Goldfarb and Yansouni, and funded by CIHR, we hosted an agenda setting meeting, entitled "Enteric Priorities in the Canadian Arctic." Key stakeholders attended a day-long meeting in Iqaluit to identify and rank priorities for enteric illness in the Canadian North. Meeting attendees included professionals from the across the Canadian Arctic, southern academic enteric illness experts, and healthcare professionals.
- ***Side Meetings at the ArcticNet Annual Scientific Meeting:*** We held several side-meetings (n = 12 meetings) with several Northern stakeholders and southern academics to build research synergies, grow partnerships, and develop our surveillance concept. These were formal meetings; as such, the project manager followed up with each stakeholder via email and circulated meeting notes.
- ***Outcome:*** Via meaningful collaboration with Northern partners, we developed and finalized the surveillance concept, methodologies, and methods.

Phase 2 Commenced: Data Collection and Empirical Research

Qualitative Data Collection:

- In consultation with Northern stakeholders, the qualitative research questions, study design, and data collection tools were developed.
- An ethnographic study design[31] will be used to follow a cohort of families (n = 10 families) for the duration of the project. A series of in-depth interviews will be conducted with each family. Families were purposively selected based on a maximum variation strategy.
- Data collection tools were developed and pre-tested in partnership with Northern stakeholders, and will capture qualitative data to characterize Inuit relationships with food, water, and pets in Iqaluit.
- Approvals were obtained from the research ethics boards at the University of Guelph, Cape Breton University, and McGill University. An application for a Nunavut Research License is currently under review.
- Data collection will commence in February 2016.
- Next steps: As outlined in our proposal, data collection will continue for the duration of the project (Year 1-3); data analysis will commence in Year 2.
- A high caliber HQP was recruited for this part of the project: Data will be collected and analysed by a research associate. This research associate has a Masters in Geography, and extensive experience conducting community-based research in Iqaluit. This position was funded through CIHR funding.

Quantitative Data Collection:

- In consultation with Northern stakeholders, the quantitative research questions, study design, and data collection procedures were developed.
- Laboratory materials and supplies are currently being purchased.
- Next steps: As outlined in our proposal, data collection is scheduled to commence in May 2016.
- High caliber graduate students were recruited to collect and anlayse data:
   - » PhD Candidate: Dr. Danielle Julien (DVM, MPH):

- Dr. Julien will examine canine enteric zoonoses in Iqaluit.
- She co-designed the canine sub-project and contributed to our proposal.
- Danielle is funded by a University of Guelph competitive scholarship.

» MSc Candidate: Anna Manore:

- Anna will examine foodborne enteric pathogens in Iqaluit.
- She has a BScH in Microbiology and experience working for the Laboratory for Foodborne Zoonoses at the Public Health Agency of Canada.
- Anna was hired as a research assistant in summer 2015, when she co-designed her MSc project; she presented her proposal as a poster at the ArcticNet Annual Scientific Meeting in Vancouver 2015.
- Since then, she enrolled in the MSc in Epidemiology program, will complete her coursework in April 2016, and begin data collection in May 2016.
- Anna is funded through a competitive Ontario Graduate Scholarship.

» MSc Candidate: Stephanie Masina:

- Stephanie will examine waterborne enteric pathogens in Iqaluit.
- Stephanie completed a BScH in Environmental Sciences, and has work experience related to monitoring water quality in Ontario.
- She worked as a research assistant in summer 2015, when she co-developed her MSc proposal.
- Since then, she enrolled in the MSc in Epidemiology program, will complete her coursework in April 2016, and begin data collection in May 2016.
- Stephanie is funded through a competitive University of Guelph scholarship.

Ongoing Knowledge Translation and Exchange (Phase 4)

- ***Team meetings:*** We held a series of two-hour meetings with the entire research team to complete Phase 1 and to begin Phase 2 (n = 4 entire team meetings).
- ***Media engagement:*** Dr. Harper was interviewed twice and highlighted the project in the interview.
- ***Annual research report:*** An annual research report was compiled for stakeholders; the report documented the process, the deliverables, and lessons learned from Year 1.
- ***Abstracts, conference presentations, scholarly posters:*** Results were shared by researchers, HQP, and Northern partners at conferences within Canada and abroad, including the annual ArcticNet Annual Scientific Meeting and meetings at the World Health Organization on surveillance in low resource settings. See publication list for details.
- ***Scholarly articles:*** While manuscripts have not been published in Year 1, we have three manuscripts in the final stages of preparation for peer-review. We anticipate that these three manuscripts will be submitted for peer-review before the end of the fiscal year.
- ***Active Website:*** A research website disseminates project outputs, including videos, updates on project progress, and research results (www.sherileeharper.com).
- ***Training and Development:*** HQP training in community-based research methods, data collection and analysis, and communications:
  - » Training in Qualitative Methods: Three Inuit will be trained in qualitative research methods (scheduled for February 2016).

   - Training in Statistical Analyses: Two Inuit will be trained in descriptive statistics, using acute gastrointestinal illness as a case study (scheduled for February 2016).
   - Graduate Student Training: Graduate students attended pre-conference workshops (e.g. ArcticNet Student Day), training workshops (e.g. week-long course in time-series data analysis at University of Prince Edward Island), and three "lab retreats" providing in-depth training in community-based research (retreat at McGill University, overnight retreat at Crieff Hills, and one-day retreat with facilitators from Cape Breton University).

Matching Funds

- ***Funding secured:***
   - In Year 1, we secured $175,800 in matching non-NCE partner funds; this is approximately twice the funds provided by ArcticNet. Additional funds were secured from CIHR.
   - In Year 2, we anticipate that we will be able to leverage three times the funds provided by ArcticNet.
- ***Funding applications:*** Our team submitted three CIHR applications (Team Grant, Project Scheme Application, and New Investigator Award) that leveraged ArcticNet funding; the CIHR decisions will be announced this spring 2016.

RESULTS

We have selected key results from our ArcticNet funded work during Year 1.

A community-based foodborne, waterborne, and zoonotic enteric disease surveillance plan was created. Through extensive stakeholder consultation, a systematic literature review of Arctic zoonoses, a Northern enteric illness agenda setting meeting, and expert elicitation, we co-developed and finalized the concept, methodologies, and methods for a surveillance program in Iqaluit. This level of stakeholder engagement and consultation was required in order to develop a monitoring system that will capture data over the funding period, but was also designed for operation after the funding period within local financial and human resources available. 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. Through this extensive stakeholder engagement and consultation, we collectively decided to focus efforts on two enteric parasites that have become emerging priorities in Iqaluit: *Giardia* and *Cryptosporidium.* Using a systems approach, we will monitor for these two parasites in food, water, and pets, as well as collaborate with Drs. Goldfarb and Yansouni to monitor these parasites in humans. While we will focus on these two parasites in this project, we will store samples for future testing of other pathogens when funds become available. While a number of pathogens and environmental exposures were considered, based on extensive stakeholder engagement, our surveillance program will involve the following:

- ***Enteric pathogens to be monitored:*** *Giardia* and *Cryptosporidium.*
- ***Food to be sampled:*** retail meat (chicken and ground beef) and country meat (claims).
- ***Water to be sampled:*** brook water (supporting Jamal Shirley's existing community-based water monitoring program) and tap water.
- ***Pets to be sampled:*** working dogs (sled dogs), pet dogs, and guard dogs.
- ***Sampling:*** Two sampling approaches will be used: (1) targeted samples will be collected weekly to explore seasonality, and (2) larger census sampling will be conducted twice per year in May (pre-thaw) and in September (end of

summer) for two years to investigate re-infection following freezing.

- ***Testing:*** Standard detection methods will be used to isolate or identify the targeted pathogens. Positive samples will be characterized further by phenotypic and molecular methods appropriate for the specific organism. This will include antimicrobial susceptibility testing, molecular typing and/or characterization of selected genes. Molecular characteristics will be compared between different sample types and samples from different places of origin, as well as between food/animal sources and humans. Comparisons will also be made, when possible, with isolates from humans, animals and food from other regions based on the reference libraries and data possessed by the Investigators and their partners. These data will be used as a tool to explore common infection sources amongst humans, animals and the environment.

There were no significant differences in the odds of enteric illness for Inuit and non-Inuit in Iqaluit. Based on our survey data (data previously collected; analysis supported by ArcticNet), we found no significant difference in the annual incidence of self-reported enteric illness between Inuit and non-Inuit in Iqaluit.

There are limited data available to make decisions about foodborne enteric pathogens in country foods. A systematic review of the literature conducted by Sargeant examined what is published in the literature about enteric pathogens in char, caribou, muskoxen, polar bears, seals, walrus, and whales. Studies generally relied on seroprevalence and had small sample sizes. Additionally, the prevalence of various pathogens varied greatly between studies. These study features makes it challenging for scientists to draw epidemiological inferences. This challenge was echoed by public health professionals and government representatives during our stakeholder consultations; stakeholders found it challenging to make evidence-based decisions about foodborne disease, and extremely challenging in enteric illness outbreak situations.

Dogs are the most common pet in Iqaluit. From our survey data (data previously collected; analysis supported by ArcticNet), we found that 38% (35-41%) of households had pets in Iqaluit. The most common type of pet was dogs (29%), followed by cats (8%), other pets (5%: e.g. rabbits, hamsters, reptiles, etc.), and working dogs (1%). While all pets can be a risk factor for enteric illness, we have decided to focus on dogs in our study based on these survey results.

While water security challenges are disproportionately experienced in Arctic communities, newspaper coverage of these challenges was limited. Using ProQuest database, we systematically searched for and screened newspaper articles published from 2000 to 2015 from four prominent Canadian newspapers: *Windspeaker*, *Toronto Star*, *The Globe and Mail*, and *National Post*. We conducted descriptive quantitative analyses and thematic analysis on relevant articles to characterize framing and trends in coverage. A total of 1382 articles were returned in the search, of which 256 articles were identified as relevant. Most stories focused on water security challenges in southern First Nation reservations, with low coverage observed for Métis (5%) and Inuit (3%) peoples. This review allowed us to understand public perception of water security challenges. For instance, considering the extremely low relative coverage of Inuit populations, public and stakeholder interest in addressing water-related issues may be undermined.

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, a MSc student further examined these data and found that there were no significant differences in odds of illness between Inuit and non-Inuit people in Iqaluit. The reason for this finding is unclear, and the pathogen testing in Year 2 will 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 have decided to focus on retail chicken and ground beef. This decision also reflects southern risk factors: chicken and ground beef are important risk factors for enteric infection, and are monitored extensively by FoodNet Canada in sentinel sites.[38] For country food, stakeholders ranked clams as an important source of enteric infection; as such, we are focusing our country food monitoring on clams collected near Iqaluit. 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 in terms of the 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;[41,35,37] however, source attribution of pathogens has been rarely conducted for parasites. As such, focusing our water sampling on *Cryptosporidium* and *Giardia* will contribute to the literature and our understanding of waterborne risks in the Arctic. Furthermore, considering the relatively limited Arctic water security media coverage, in Year 2 we hope to engage with the media to bring attention to water security challenges in the Canadian North.

Zoonotic enteric infection. Stakeholder concern about dogs as a source of enteric infection is supported by previous research that identified puppies as an important risk factor for enteric illness in the Arctic[37] and elsewhere in Canada.[8–10,16,43] Indeed, dogs are known to asymptomatically carry several pathogens that could cause enteric illness in humans.[44–46] Our stakeholders also hypothesize that pathogen loads in dogs in the North differ from the South. For example, *Giardia* parasites are grouped within distinct assemblages, some of which are species-specific and some of which infect multiple species. In southern populations, dogs almost always carry dog-specific *Giardia* assemblages and human disease is unrelated. In some Canadian First Nations, however, some scholarly evidence suggests that this may not be the case.[47] In communities with wastewater treatment infrastructure challenges, human assemblages of *Giardia* are common in dogs because they are exposed to human sewage.[47] As such, dogs are a potential source of human infection, and vice versa. Our end-users believe that this type of unusual pathogen source attribution might also be true in Northern Canada. Therefore, our plans to test dogs for fecal shedding of *Cryptosporidium* and *Giardia* will help us understand whether dogs are reservoirs in Iqaluit.

CONCLUSION

We have successfully designed a foodborne, waterborne, and zoonotic enteric illness surveillance system in collaboration with Northern stakeholders. Our surveillance design is grounded in scientific evidence and Inuit traditional knowledge, will provide data that are comparable to national surveillance programs, and is culturally appropriate and locally relevant. We are ending year ahead of schedule: we have completed Phase 1 (e.g. finalized our surveillance concept, methodologies, and methods), and we have began Phase 2 (Data Collection and Empirical Research) ahead of schedule. We have:

- Completed Year 1 project milestones and deliverables (as outlined in our proposal)
- Trained three Inuit and four graduate students
- Presented 10 presentations at conferences
- Published one manuscript, and prepared three manuscripts for peer-review
- Highlighted the project in two media interviews
- Secured $175,800 in matching non-NCE partner funds; this is approximately twice the funds provided by ArcticNet. Additional funds were secured from CIHR.

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Researchers:

- **Ashlee Cunsolo Willox,** PhD, Canada Research Chair & Assistant Professor, Cape Breton University
- **Scott Weese,** DVM, DVSc, Dipl ACVIM, Professor, Department of Pathobiology, University of Guelph

Collaborators:

- Maureen Baikie, BScPhm, MD, MSc, FRCP(C), Chief Medical Officer of Health, Government of Nunavut
- Victoria Edge, MSc, PhD, Manager, Public Health Agency of Canada
- James Ford, MSc, PhD, Department of Geography, McGill University
- Lea Berrang-Ford, MSc, PhD, Department of Geography, McGill University
- Jamal Shirley, Manager, Nunavut Research Institute
- Inez Shiwak, Research Associate, Rigolet Inuit Community Government
- Jack Shiwak, AngajukKâk, Rigolet Inuit Community Government
- Michele Wood, B.A., M.I.M., Department of Health and Social Development, Nunatsiavut Government

Students/Highly Qualified Personnel

- Lindsay Day (MSc Candidate, University of Guelph/Cape Breton University)
- Danielle Julien (PhD Student, University of Guelph)
- Anna Manore (MSc Candidate, University of Guelph)
- Stephanie Masina (MSc Candidate, University of Guelph)
- Anna Bunce (Project Manager)

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Wildlife Diseases Important for Human Health and Food Safety in the Changing Environment of the Eastern Subarctic

Project Leaders

Patrick Leighton (Université de Montréal); Emily Jenkins (University of Saskatchewan)

Network Investigators

Philippe Gachon (Université du Québec à Montréal)
Alvin Gajadhar (Canadian Food Inspection Agency)
Stéphane Lair (Université de Montréal)
Nicolas Lecomte (Université Laval)
Francis Lévesque (Université du Québec en Abitibi-Témiscamingue)
Dawn Marshall (Memorial University of Newfoundland)
Nicholas Ogden (Université de Montréal)
André Ravel (Université de Montréal)
Craig Stephen (University of Saskatchewan - Canadian Wildlife Health Cooperative)
Hugh Whitney (Government of Newfoundland and Labrador)

Collaborators

Ellen Avard (Makivik Corporation)
Suzanne Bastian (Oniris - École nationale vétérinaire, agroalimentaire et de l'alimentation Nantes-Atlantique)
Denise Bélanger (Université de Montréal)
Dominique Berteaux (Université du Québec à Rimouski)
Mario Brisson (Nunavik Regional Board of Health and Social Services)
Brent Dixon (Health Canada)
Julie Ducrocq (Université de Montréal)
Christine Fehlner-Gardiner (Canadian Food Inspection Agency)
Barrie Ford (Makivik Corporation)
Josiane Houle (Université de Montréal)
Pauloosie Kasudluak (Community of Inukjuak)
Mélanie Lemire (Université Laval)
Benoit Lévesque (Centre de Recherche du Centre hospitalier de l'Université Laval)
Ariane Massé (Ministère des Forêts, de la Faune et des Parcs)
Peter May (Makivik Corporation)
Susan Nadin-Davis (Canadian Food Inspection Agency)
Susan Nulukie (Nunavik Research Centre)
Stas Olpinski (Makivik Corporation)
Isabelle Picard (Ministère Agriculture, Pêches et Alimentation (MAPAQ))
Erin Rees (University of Prince Edward Island)
Manon Simard (Makivik Corporation)

HQP

Nicholas Bachand, Doctoral Student (University of Saskatchewan)
Mathilde Mercat, Doctoral Student (Université de Montréal)
Hélène Déry, Masters Student (Université de Montréal)
Marie-Christine Frenette, Masters Student (Université de Montréal)
Cécile Aenishaenslin, Post-Doctoral Fellow (Université de Montréal)
Audrey Simon, Post-Doctoral Fellow (Université de Montréal)

Northern HQP

Johnny Arnaituk Arnaituk, Northern Research Staff (Regional Nunavimmi Umajulivijiit Katujiqatigininga (regional HTO))
Pauloosie Novalinga, Northern Research Staff (Regional Nunavimmi Umajulivijiit Katujiqatigininga (regional HTO))
Salamiva Weetaltuk Weetaltuk, Northern Research Staff (Local Nunavimmi Umajulivijiit Katujiqatigininga (local HTO) - Kuujjuarapik)
Alexander Flynn, Northern Student (Memorial University of Newfoundland)

ABSTRACT

The proposed project integrates traditional knowledge from communities in Nunavik and Nunatsiavut with a combination of disciplines (epidemiology, microbiology, population genetics, behavioural ecology, landscape ecology, disease modelling, and anthropology) which will help to better assess and predict the risk of exposure to diseases relevant to the health of wildlife and local communities. We will target a directly transmitted viral zoonosis (rabies) and two food-borne parasites (*Trichinella* and *Toxoplasma*) with known potential to negatively impact human and animal health in the North. We will also work with communities and Hunter/Trapper Organizations (HTOs) to identify their concerns, which may highlight other priorities. Results will be shared with collaborators (an array of public health personnel and policy makers), participating communities (through environmental health officers, annual presentation to HTOs), and high risk populations for exposure (e.g. school children) through educational outreach programs.This project will provide baseline information that communities, public health personnel, wildlife managers, and policy makers can use to determine the role of wildlife in human exposure to zoonoses (and vice versa), and to develop culturally appropriate control and surveillance strategies for diseases affecting the health of both wildlife and people in the Canadian Eastern Subarctic.

KEY MESSAGES

- Wildlife are an important source of food and income in northern communities, but are also a source of human exposure to diseases.
- Rapid climate warming across the Arctic, and particularly in the Eastern Subarctic, is driving rapid ecosystem change, with a potential impact on the ecology of wildlife diseases and human exposure to these diseases.
- Our project aims to assess the current health risks presented by wildlife diseases for communities in the Eastern Subarctic through community consultation and testing for diseases in hunted wildlife, and to estimate the impact of rapid regional climate change on these health risks through statistical analyses and modelling.
- Toxoplasmosis is an important human disease caused by food-borne parasites; our project is monitoring hunted meats in three Nunavik communities for toxoplasmosis, focusing on wildlife species suspected to be involved in transmission: ringed seals, ptarmigans and Canada geese.
- Rabies is a lethal disease with regular outbreaks in arctic and red (coloured) fox populations posing a threat to the health of dogs and people; our project is monitoring rabies and toxoplasmosis in trapped foxes from four communities in Nunavik, three communities in Nunatsiavut and two communities in southern Labrador.
- People acquire wildlife diseases through direct contact with wildlife, but also indirectly from domestic dogs that contact wildlife; our project is working in partnership with the community of Kuujjuaq to carry out community consultations and monitor human-dog-wildlife interactions in order to better understand the routes and risks of human and dog exposure to wildlife disease.
- Climate warming is alterning wildlife ecology, including where and when parasites are transmitted and wildlife disease outbreaks occur; our project is combining cutting-edge models of wildlife disease epidemiology with state-of-the-art climate projections for the Eastern Subarctic to predict how human exposure to food-borne parasites (*Toxoplasma* and *Trichinella*) and viruses (rabies) is likely to change in the coming years.
- Results from Year 1 monitoring and community consultation suggest that the risk of wildlife disease is real and present in all of our partner communities, but that risk perceptions are highly variable among individuals and communities.

- Continued monitoring will be important to establish a multi-year baseline for human exposure to wildlife diseases in the Eastern Subarctic, providing important information for public health management and an opportunity to discuss and integrate wildlife disease risk management in communities across the region.

OBJECTIVES

In 2015-2016, we addressed the following objectives, as laid out at the beginning of the project:

1. Detect and characterize diseases in wildlife populations with close contact with human settlements at a broad regional scale.
2. Better characterize the human/wildlife interface by assessing contact rates and potential routes of exposure between people and wildlife at the individual community level.
3. Develop models to identify important risk factors for wildlife and human exposure, to predict future disease risk for people and wildlife within a changing climate, and to evaluate options for risk management.

INTRODUCTION

Wildlife are valued for cultural, nutritional, economic, and ecological reasons in northern communities across Canada (Chan et al. 2006). In 2004, Inuit of Nunavik consumed harvested wildlife more than five times per week and country foods represented an important dietary source of high quality protein (Blanchet and Rochette 2008). Although harvested wildlife represents an important source of food security, it may also be a source of human exposure to zoonoses (diseases that transmit between animals and people) (Cutler et al. 2010). In addition, frequent interaction with wildlife in northern communities increases the risk of direct transmission of zoonotic diseases such as rabies from infected wildlife to domestic animals and people. Climate warming is a particularly important driver of ecosystem change in the Arctic, along with anthropogenic activities such as increasing shipping activity, resource development, and increasing human and companion animal populations (Cramer and Yohe 2014). The primary objective of our project is to better understand the current health risks presented by wildlife diseases in Arctic communities, and how these are likely change over time in a rapidly warming climate.

Zoonotic diseases of wildlife are a significant source of human illness in communities of the Canadian Arctic (Jenkins et al. 2012). Residents of the Eastern Subarctic are at higher risk of exposure to food-borne parasites such as *Toxoplasma* and *Trichinella* compared to the general Canadian population. In Nunavik, for instance, the seroprevalence of toxoplasmosis is 2-10 times higher than in the rest of the Canadian Arctic (Messier et al. 2009). Moreover, epidemiological studies suggest that some wildlife species (especially marine mammals) and methods of food preparation are an important source of human exposure to several zoonoses in the North (Messier et al. 2009).

Rabies is a 100% lethal zoonotic viral disease that is endemic in the Arctic, posing a significant and ongoing public health threat to its inhabitants. Worldwide, most people are exposed to rabies virus through a bite from domestic dogs. In the Eastern Subarctic, people can be infected through direct contact with infected wildlife (primarily arctic foxes (*Vulpes lagopus*), the main reservoir for the disease, but also increasingly red foxes (*Vulpes vulpes*)), or through the bite of domestic dogs that acquired rabies from wildlife. There are significant risks of exposure to rabies in the Inuit communities of Nunavik and Nunatsiavut as rabies outbreaks are reported in these communities on a frequent yet seemingly unpredictable basis. In some cases the outbreaks can be very extensive involving significant numbers of animals from multiple communities. The risks of virus transmission are enhanced by the fact that the dogs in Eastern Subarctic communities are often unvaccinated and free-roaming, facilitating interaction with foxes that have come into communities. Little is known about the complex epidemiology of Arctic rabies, especially how the rabies virus persists in such low-density and highly cyclical wildlife populations (Mork and Prestrud 2004).

There is significant concern about the effects of climate change on the amplification of endemic diseases in the Arctic, including the three zoonoses addressed in this proposal (Parkinson et al. 2014). Toxoplasmosis is considered the most important parasitic zoonosis in the North American Arctic (Hotez 2010), and its ecology and transmission are sensitive to changing climate conditions, especially those affecting snow melt and precipitation patterns (Simon et al. 2013). Rabies is the most important wildlife disease for public health in the Canadian Arctic (Jenkins et al., 2012), and its ecology is also linked to climatic conditions, with effects of climate warming on fox movement and contact rates, population dynamics linked to perturbation of population cycles of lemmings (important prey), and displacement of cold-climate specialized arctic foxes by their southern competitor the red fox (Simon et al. 2014).

Our project specifically addresses gaps in our understanding of the ecology and transmission dynamics of wildlife diseases of public health importance in order to understand: 1) how zoonoses are transmitted amongst wildlife and how people are exposed, 2) how wildlife, domesticated animals and people interact in a changing environment, 3) how diseases spread from north to south (i.e. arctic fox rabies) and from south to north (such as toxoplasmosis), and 4) how disease transmission may be affected by a warming, more climatically variable, and more interconnected Arctic.

ACTIVITIES

Project activities for 2014-2015 were focused around building contacts and networks of participating communities, planning and carrying out the first collection of wildlife samples to establish baseline information on disease prevalence, collecting community data and traditional knowledge through interviews, surveys and informal discussions, and communication activities to share research plans and outcomes with communities as well as among different working groups within our research project.

In this first year of the project, we carried out several key structuring activities in Year 1 that helped align research activities with specific project objectives, and co-ordinated communication, resource use, and HQP supervision. The first of these was to establish four thematic working groups, each with a co-ordinator and mailing list: 1) Food safety, 2) Fox genetics and rabies, 3) People, dogs and wildlife and 4) Climate and disease modeling (Figure 1). The second was to establish a communication plan, which lead to the organization of two project-wide video-conferences (June 2015 and October 2015), several project meetings at the ArcticNet ASM, and the organization of a project-wide in-person meeting and workshop that will take place in April 2016. The third was a major investment of time and resources in developing a strong and dedicated network of participating communities and northern partners through frequent travel to the north throughout the year, recruitment and training of community co-ordinators, and active project follow-up by telephone and email.

1. Food safety

Year 1 involved significant progress in a) community consultation and engagement, b) field collections, and c) laboratory analyses for the food safety component:

a. Although all communities expressed interest in participating in the project in our initial discussion with representatives at the Annual

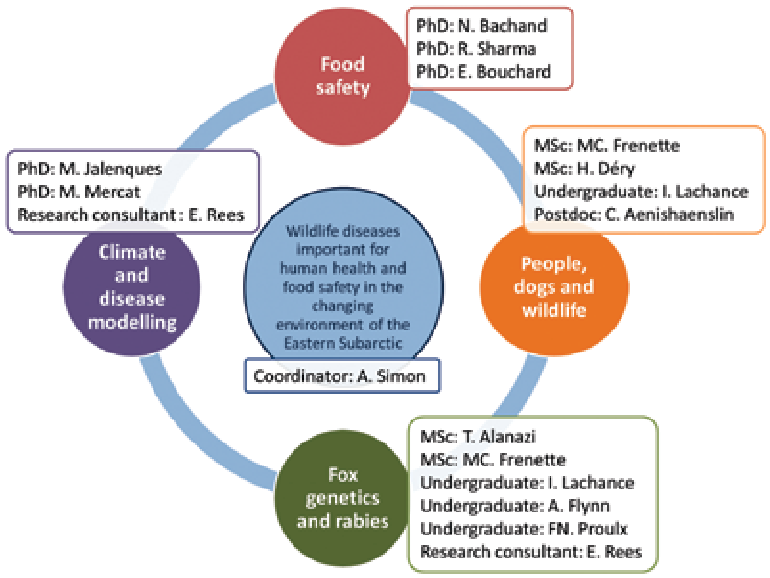

Figure 1. Diagram of project thematic working groups and associated HQP.

Hunter Trapper Organization (HTO) Meeting in November 2014, we targeted three communities (Kuujjuarapik, Inukjuak, and Puvirnituq) based on their high levels of exposure to toxoplasmosis in the last Inuit Health Survey, and their high levels of interest in participating in the study. We also drew extensively on TEK to target wildlife species of most interest to the communities and the most commonly consumed, exploring marine and terrestrial ecosystems as well as migratory and resident wildlife. At the Annual HTO Meeting in November 2015, we were invited to provide a progress report on the wildlife sampling component of this project to all 14 Nunavik HTO representatives. The meeting presentation was aired on the regional radio. Overall, participating communities were happy with the project and curious about any results obtained so far. People were told that results would be available by the next annual HTO meeting.

b. Three sample collection trips were made in May, Aug-Sept, and November 2015, timed to capitalize on seasonal availability of wildlife species of interest. The last collection trip was combined with administration of a survey on risk factors, risk perception, and TEK regarding parasites in wildlife, for which we had a high level of community participation. Survey analyses are underway.

c. We have successfully developed laboratory capacity by the end of November 2015 to perform a highly sensitive technique (magnetic capture DNA extraction) for detection of *Toxoplasma gondii* in tissues, and are now, to our knowledge, the only lab in Canada offering this service, which is the new European food safety standard (Photo 1). N. Bachand traveled to Holland in March 2015 to learn the technique. Laboratory analyses are currently underway, and results are anticipated for spring 2016 (Table 1).

2. Fox genetics and rabies

In Year 1 we made significant progress in d) engaging a network of participating communities engagement, e) field collection of trapped foxes, f) genetic analyses for collected fox samples, and g) statistical analysis of rabies data:

d. We spent spring and summer of 2015 establishing contacts with participating communities through the field visits by N. Bachand to each community, and we presented the fox genetics and rabies project at the Regional Nunavimmi Umajulivijiit Katujaqatigininga (RNUK) meeting on November

Photo 1. Magnetic Capture Laboratory in Saskatoon, Canada. Source: N. Bachand.

16, 2015 to obtain input from local communities' representatives and HTO. In addition, we developed a new partnership with the James Bay Cree communities, The Cree Trappers Association, and the Ministère des Forêts, de la Faune et des Parcs (A. Massé) to extend fox sampling activities to the south of Nunavik, covering the suspected pathways of rabies spread from Nunavik to southern Quebec. Five communities are participating in the sampling (Chissasibi, Wemindji, Waskaganish, Waswanipi, and Mistissini) with a target total sample size of 84 specimens.

e. Fox sampling began in winter 2014-2015 as we were able to obtain previously trapped fox samples from two communities in Labrador at the start of the project (41 specimens). Full-scale sampling began in fall 2015 in the four communities of Nunavik and five communities of Nunatsiavut and southern Labrador. Undergraduate student (I. Lachance) developed and prepared the material and protocol for the Year 1 fox field collection as well as education tools about wildlife diseases.

f. Genetics work began with performing finer-scale genetic analyses on samples previously collected during the 2012-2013 rabies outbreak across Canada in order to use these tools for analysing the specimens collected during this current project. Specifically, we employed NSERC-USRA student (A. Flynn) during May-August 2014 to collect 9-locus microsatellite profiles from 140 arctic foxes and 146 coloured foxes, including 52 rabies-positive animals, for which DNA extraction and mitochondrial DNA analysis had been performed previously. We also conducted preliminary analyses of microsatellite data for presentation at ArcticNet ASM 2015. We recruited MSc student (T. Alanazi; started January 2016) to continue and expand genetic characterization both of existing and of newly collected samples.

g. We analysed rabies cases collected through the passive surveillance system operated by the Canadian Food Inspection Agency (CFIA) in Yukon, Northwest Territories, Nunavut, Nunavik and Labrador from 1953 to 2014, then providing the first overview of the spatio-temporal distribution of animal rabies cases across the Canadian Arctic. These analyses explored the ecological and behavioural mechanisms

Table 1

Summary of activities	Location	Date
Meeting with Makivik Corporation	Montreal, Qc	October 6 2014
Meeting with Regional Nunavik HTO*	Kangiqsualjjuaq, Qc	November 24-28 2014
First wildlife sampling season	Nunavik, Qc	May 1 – May 20, 2015
Second wildlife sampling season	Nunavik, Qc	Aug 25-Sept 15, 2015
Questionnaire finalized & translated	Saskatoon, Sk	Oct 10 2015
Preliminary lab analyses (serology)	Saskatoon, Sk	Oct 20-27, 2015
Third wildlife sampling season	Nunavik, Qc	Nov 9-Nov 26, 2015
Survey work	Inukjuak, Qc	Nov 10-13, 2015
2nd annual Nunavik HTO meeting	Nunavik, Qc	Nov 17-Nov 21, 2015
Magnetic Capture technique pilot project	Saskatoon, Sk	Dec 4-5, 2015
Samples sent to Health Canada lab (PCR results pending)	Ottawa, On	Dec 7, 2015
ArcticNet Annual meeting, poster & oral	Vancouver, BC	Dec 7-11, 2015
Preliminary Toxo tissue detection analyses	Saskatoon, Sk	Jan 5 – present (2016)

underlying the onset of rabies outbreaks in the fox populations (Table 2).

3. People, dogs and wildlife

In 2015, we went to Kuujjuaq four times to meet with local organizations, present the project and build interest, trust and participation, with a 5th trip planned in March 2016 to return survey results to the community. The following organizations were met and all supported or even participated in activities: the Municipality of Kuujjuaq (participant), the Nunavik Research Center (participant), The Kativik Regional Government (support) and the Nunavik Board of Public Health (support). The main activity was the undertaking of a survey on dogs among dog owners in Kuujjuaq, including mushers. The survey aims at characterizing dog demographics, health, feeding, housing, relationship with wildlife as well as perception about dogs. In addition, MC Frenette spent two months at the Karrak Lake research station, NU, learning fox live-capture techniques and field-testing dog and wildlife contact monitoring methodology using camera traps (Table 3).

4. Climate and disease modelling

In 2015, we focused on adapting an existing simulation model developed for the management of raccoon rabies in southern Ontario, the Ontario Rabies Model (ORM), for use in modelling rabies in the Arctic. Key steps in this process included hypothesis development and testing using a Suceptible-Exposed-Infected (SEI) model of rabies in the Arctic, validating ORM for modelling fox rabies using the extensive dataset on red fox rabies spread in Ontrario, and ongoing adaptation of the model code and parameters to take into account large-scale movements and low densities of arctic and red foxes in our study region. A significant step was the acquisition of the necessary computing ressources for large-scale modelling through a successful submission to the 2016 Compute Canada Resource Allocation Competition (RAC). We also built research partnerships for modelling climate impacts on toxoplasmosis and trichinellosis epidemiology in preparation for the PhD project of M. Mercat on this subject (Table 4).

RESULTS

1. Food safety

1.1 Toxoplasmosis in hunted wildlife

Wildlife samples were received at the University of Saskatchewan starting in late October 2015, at which time preliminary serological tests were done. The magnetic capture DNA extraction on Nunavik wildlife samples started in January 2016.

- Successful in engaging key communities with high exposure to toxoplasmosis based on Inuit Health Survey results – important to narrow in on these communities due to logistics and the higher sample honoraria than initially anticipated.

Table 2

Summary of activities	Location	Date
Analyses of microsatellite data	St. John's, NL	May-August 2014
Fox field collection (pre-project)	Nunavik/Labrador	January-April, 2015
Fox carcass sub-sampling protocol tested	St-Hyacinthe, Qc	April 15-30, 2015
Statistical analysis of spatio-temporal determinants of rabies cases in the Canadian Arctic	St-Hyacinthe, Qc	April – Sept. 2015
Development and translation of field protocol; preparation of sampling kits	Quebec, Qc	April-October 2015
Fox field collection season year 1	Nunavik/Labrador	Oct. 2015-April 2016
Project presentation at RNUK/HTO meeting	Kuujjuaraapik, Qc	November 16, 2015
Preliminary fox genetic results and analysis of rabies cases presented at ArcticNet ASM	Vancouver, BC	December 7-11, 2015
Development of information fact sheet about rabies and other wildlife diseases	Quebec, Qc	December 2015-March 2016

Table 3

Summary of activities	Location	Date
Kuujjuaq trip 1 – Community presentations	Kuujjuaq, Qc	March 9-11, 2015
Kuujjuaq trip 2 – Dog survey planning	Kuujjuaq, Qc	May 4-7, 2015
Dog survey development	St-Hyacinthe, Qc	September 2015
Kuujjuaq trip 3 – Dog survey pilot	Kuujjuaq, Qc	October 13-16, 2015
Kuujjuaq trip 4 – Dog survey; wildlife pilot	Kuujjuaq, Qc	November 25 to December 3, 2015
Field testing fox interaction monitoring	Karrak Lake, NU	June-Aug 2015
Kuujjuaq trip 5 – Dog survey results returned to community	Kuujjuaq, Qc	March 1-5, 2016

Table 4

Summary of activities	Location	Date
ORM validation with red fox in Ontario	St-Hyacinthe, Qc	January – June, 2015
Hypothesis testing with dynamic SEI model	St-Hyacinthe, Qc	April – Dec. 2015
ORM parameterization for arctic fox	St-Hyacinthe, Qc	April – Aug. 2015
ORM extension and adaptation	St-Hyacinthe, Qc	Sept. 2015 – current
Preliminary modelling results presented at ArcticNet ASM	Vancouver, BC	December 7-11, 2015
30 core years secured with Compute Canada	St-Hyacinthe, Qc	December 2015

- Successful in obtaining and receiving samples from wildlife species commonly consumed in Nunavik.
- Successful in high levels of participation in one community for survey exploring risk factors, risk perception, and TEK for parasites in wildlife consumed in Nunavik.

Wildlife samples received at the University of Saskatchewan as of December 2015 (Table 5).

Serological analyses (Modified Agglutination Test) (Table 6).

1.2 Local knowledge and risk perception of parasites in hunted wildlife

1.2.1. Survey objectives

1. Assess general knowledge of wildlife parasites;
2. Assess knowledge of food safety recommendations and practices with respect to the handling and consumption of hunted wildlife carcasses;
3. Assess exposure of local people to raw ringed seal heart, liver and meat (to do an exposure assessment with respect to *Toxoplasma gondii* – but which will also be applicable to other zoonotic foorborne pathogens found in these seal tissues);
4. Assess local risk perception with respect to the health impact of foodborne parasites from wildlife species tradionally consumed in Nunavik.

1.2.2. Survey participants (response) (Table 7)

This represents 15% of the Inukjuak population. A total of 112 households were included which represents 40% of all households in Inukjuak.

1.2.3. Preliminary survey results

Although analyses are just starting, general findings include the following:

- Based on ninr questions which addressed general knowledge of wildlife parasites (e.g. transmission routes, symptoms of foodborne parasitic diseases, etc.), 71% of survey respondents had a low to moderate knowledge score.
- Only 13% of survey respondents had heard of Toxoplasma compared to 25% of respondents who had heard of *Trichinella*.
- Almost 60% of respondents reported that they consume raw parts while processing the carcass of hunted wildlife.

- About 70% of survey respondents reported that they consumed seal liver in the last year (99% of these respondents consumed it raw), compared to 81% of survey respondents who consumed seal meat (76% of these respondents consumed it raw) and 18% of respondents who ate seal heart (80% of these respondents consumed it raw).
- Almost 50% of respondents believe that several wildlife species commonly consumed in Nunavik (seals, caribou, geese and ptarmigan) could be infected with parasites. Similarly, about 50% of survey respondents are concerned that parasites from wildlife could harm their health.
- About 43% of respondents reported that they are highly likely to become diseased due to a foodborne parasite from wildlife in the next year.

2. Fox rabies and genetics

2.1 Virus variant characterization and microsatellite genetic structure of arctic and red fox populations

Previous work on specimens collected during the 2012-2013 outbreak identified three different rabies virus variants circulating in wildlife in northern Canada during that period (Figure 2). Variant 3.2b was very confined geographically to a region of the Northern Territories in western Canada while variant 3.1a was recovered from far northern regions and western Canada. In contrast, variant 3.2a was broadly distributed across northern Canada and appeared to be the only type circulating in the eastern region of the country. Rabies cases recorded in Labrador were the result of a single incursion of a virus variant predicted to have emerged over the last 8-12 years, diverging from a virus variant responsible for a 2006-2009 outbreak observed in the Nunavik region.

Table 5

Wildlife Species	Year 1 (received)	Year 2 (expected)
Ringed seals	45	30
Canada geese	72	50
Ptarmigan	122	110
Foxes	30	90

Microsatellite data analysis for arctic and red foxes collected across Canada during the same outbreak revealed significant genetic structure at this spatial scale. Here we present microsatellite results and compare them with earlier mtDNA results:

- Among 140 arctic foxes, gene diversity ranged from H = 0.74 in Québec to H = 0.79 in Rankin Inlet (average ~ 0.76). STRUCTURE analysis identified one as the most likely number of genetic clusters, the same as was found with mtDNA. Pairwise measures of differentiation among localities ranged from F_{ST} = 0 ~ 0.02; they were highest and significant in comparisons of MB to NU locations and among NU locations (Igloolik, Baker Lake, and Rankin Inlet).

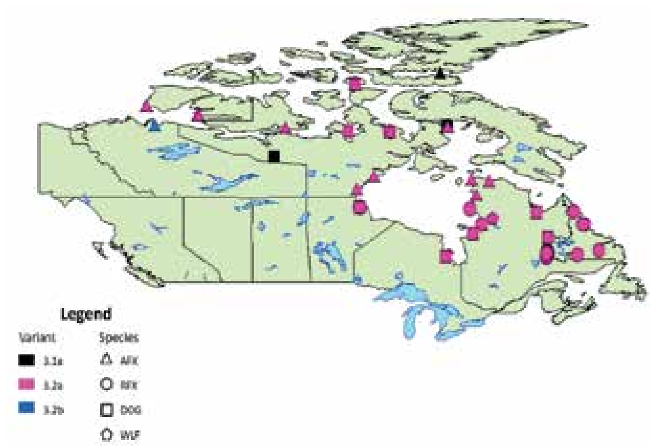

Figure 2. Map of Canada showing the location of the 2012-2013 rabies isolates (n=64). Symbols indicate the species as follows: AFX- arctic fox, RFX- red fox, DOG- dog, WLF-wolf. Colour indicates the assigned variant. In some cases a single symbol refers to multiple isolates at the same location.

Table 6

Wildlife species	Number received	Number analyzed	Positive	Suspect Positive	Negative
Ringed seals	45	2	0	0	1
Canada geese	72	39	1	2	36

Table 7

	Total	18-34 yrs	35-49 yrs	50+ yrs
Men	87	39	35	14
Women	88	35	26	26
Total	175	74	61	40

- Among 146 coloured foxes, gene diversity ranged from H = 0.60 to H = 0.69 (average ~ 0.65). Similar to mitochondrial DNA, STRUCTURE analysis of microsatellites indicated 3 genetic clusters, and differentiated LAB/QC populations from MB/NU/NT. Pairwise measures of differentiation among localities ranged from F_{ST} = 0 ~ 0.10 (average ~ 0.031), and were mostly significant. They were highest in comparisons of Cartwright LAB, to other locations.

2.2 Rabies in arctic and red foxes in the Canadian Arctic

Rabies cases were found in all Arctic regions of Canada except Yukon, with a north south gradient in the proportion of positive cases (Figure 3).

Outbreaks were relatively synchronous among species (arctic fox, coloured fox, and dog). A temporal synchronicity in the outbreaks occurred in Nunavik and Labrador, suggesting an epidemiological connection in the transmission of rabies between these two provinces (positive correlation r = 0.45 with a lag of one year) (Figure 4).

2014-2015 appeared to be a rabies outbreak year with 41 animals submitted by provincial authorities to the CFIA from Nunavik and Labrador for rabies testing, of which 18 (44%) tested positive (Figure 5).

We found correlations between the fox densities and the rabies outbreaks, a seasonal effect with more reported cases in Fall and Winter than in Spring and Summer, and a correlation between the sea-ice concentration (used by fox to disperse and forage) and the rabies outbreaks. These analyses gave some insights on how density and dispersal of fox populations via sea-ice could drive rabies transmission dynamics.

2.3 Collection of fox samples

Rabies testing will be carried out on these samples in the coming months (Table 8).

3. *People, dogs and wildlife*

Sixty-seven people participated to the dog survey in Kuujjuaq in November and December 2015. The data analysis has started and is planned to be finalized in February with feedback to Kuujjuaq local partners and people before the end of March 2016.

- 64% of the participants were women, 54% of the participants were beneficiary of the James Bay and Northern Quebec Agreement (JBNQA), and

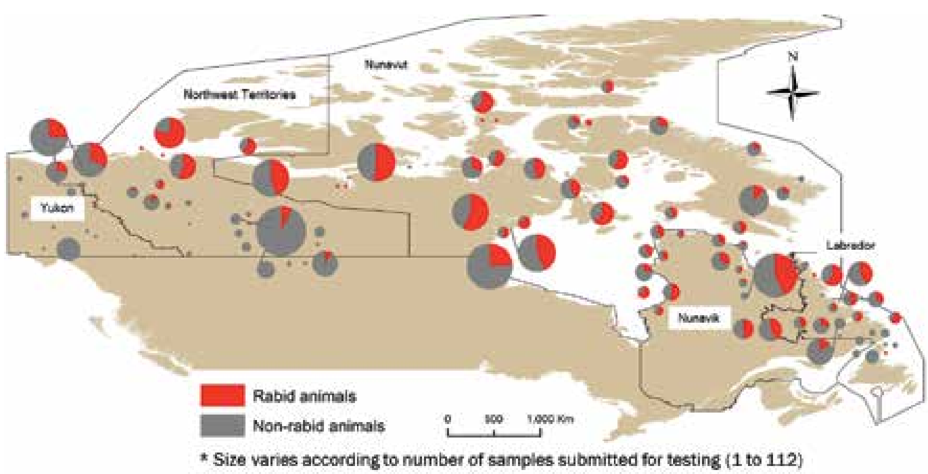

Figure 3. Map of Northern Canada showing the proportion of rabid animals found in the municipalities between 1985 and 2014.

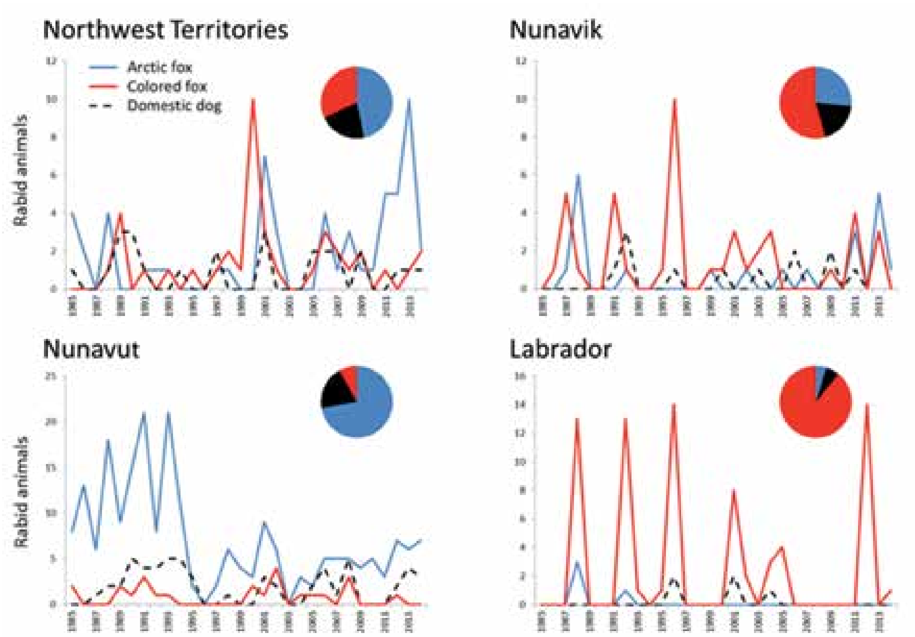

Figure 4. Temporal series of rabid animals (arctic and red foxes, and dogs) in Nunavut, Northwest Territories, Nunavik, and Labrador from 1985 to 2014.

the mean lifetime spent in Nunavik was 21 years (Range: 0.5 to 60 years).

- Demographic and health data were collected for the 105 dogs owned by the respondents. Forty-six percent were female, 36% of dogs were neutered and 78% were vaccinated aginst rabies (at least once in their life).

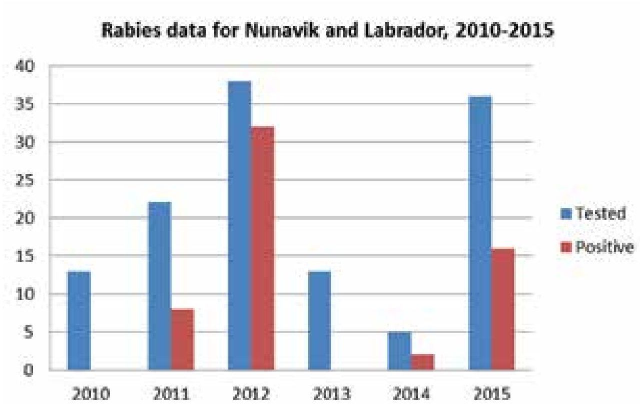

Figure 5. Bar graph of the annual number of submissions and positive samples from 2010 to 2015 in Nunavik and Labrador.

- The most frequently observed species interacting with dogs was raven, with 52% of the participants who had previously observed their dog interacting with them to chase, play or fight (42% reported observing such interactions everyday). Nineteen percent reported interactions with porcupines, but only sporadically. Other interactions of dogs with wildlife were rarely observed (white foxes: 4.5%, red foxes: 9%, wolves: 4.5% bears: 6%).

4. Climate and disease modelling

4.1 Arctic fox rabies dynamics and persistence in northern Canada

We built a compartmental SEI (Susceptible, Exposed and Infected) model (Figure 6) that aimed to 1) identify the general characteristics of the transmission of the rabies virus and the importance of different parameters in the persistence of rabies in arctic foxes, and 2) investigate the role of arctic fox population cycling and the resulting degree of interspecific interaction with red foxes on the transmission and persistence of rabies.

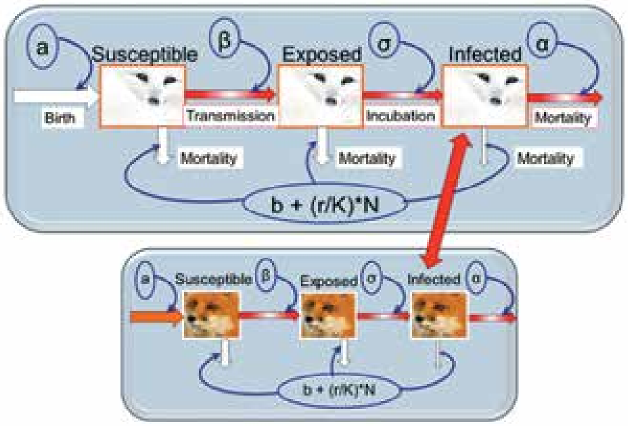

Figure 6. Compartmental SEI (Susceptible, Exposed and Infected) model simulating the transmission of the rabies virus in a population of arctic foxes interacting with a population of red foxes (a: average per capita density-independent birth rate; β: transmission coefficient; σ: per capita rate from the incubating class to the infectious state; α: death rate of rabid foxes; b: average per capita density-dependent death rate; r: population growth rate; K: carrying capacity; and N: size of the fox population).

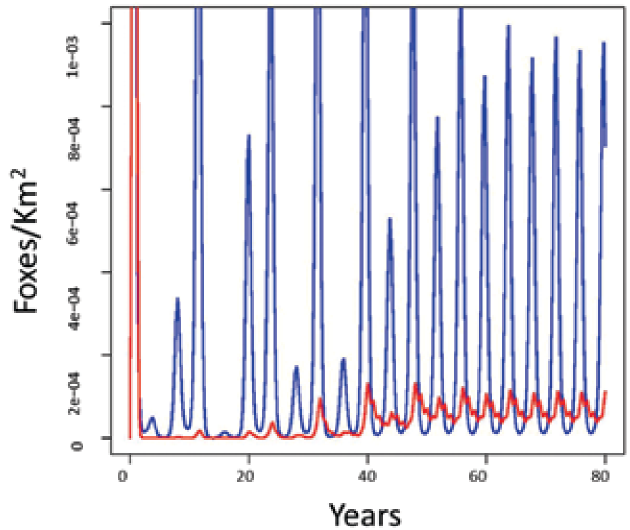

Figure 7. Annual density of rabid arctic foxes interacting with red foxes (blue vs. red curves) in a seasonal environment simulated by the compartmental SEI (Susceptible, Exposed and Infected) model.

1. The model parametrized with empirical values indicates that rabies is unlikely to persist within the arctic fox population, because the susceptible host density is too low.
2. Environmental seasonality transformed the enzootic equilibrium into an epizootic cycle with the periods and intensity of rabies infection varying as a function of the strength of seasonal forcing. In the case where rabies virus could not be maintained in the population of red foxes alone, a low rate of rabies transmission between the two fox species was enough to generate cyclicity of rabies incidence in the population of red foxes (Figure 7).

4.2 Rabies outbreak simulations for the Eastern subarctic

The goal of this project is to develop a model simulating arctic fox rabies in arctic and red fox populations of northern Canada. The progress of this project is summarized into three steps: (1) Review scientific literature to assess the potential for an existing model, the Ontario Rabies Model (ORM) as originally parameterized for raccoon populations and raccoon rabies, to simulate arctic fox rabies; (2) Perform mini-experiments to test the ability of ORM to represent the arctic fox rabies system; and (3) Begin adapting ORM to more accurately simulate arctic fox rabies, resulting in a new model to be called the Arctic Rabies Model (ARM).

1. *Literature Review to determine the similarities and differences between arctic fox and racoon rabies ecologies that drive the respective disease dynamics.* A key difference is that the resource-poor northern environment, relative to higher quality raccoon habitat in temperate regions, highly influences fox movement and interaction patterns, and reproduction and survival rates, especially in arctic and red foxes. Therefore, in adapting ORM to become ARM, habitat quality will be defined to influence these population processes and behaviours. ARM will also enable a wider range in host movement behaviours for

frequency and distance. Furthermore, ARM will enable simultaneous modelling of multiple host species (i.e. arctic and red foxes).

2. *Mini-experiments to test the feasibility of using the ORM structure to model arctic fox rabies.* A key challenge was simulating a stable fox host population, which could also maintain rabies, with a density that was 10-fold lower than originally designed for when simulating raccoons in ORM. We achieved observed arctic fox population and rabies dynamics by: a) increasing the size of landscape cells structuring population and epidemiological processes, b) increasing the probability of rabies transmission, and c) increasing the incubation period (Figures 8 and 9).
3. *Adapting ORM to become ARM.* We are in consultation with the original ORM developers and software engineer to begin our changes to ORM for becoming ARM. ORM is programmed in the object-oriented language c#. The core ORM structure will remain largely unchanged. The major developments will be adding new classes of animals, that is, arctic and red foxes, to the existing raccoon class. Furthermore, the user-interface will be updated to enable more extensive user-defined parameterization of the host ecology.

DISCUSSION

1. Food safety

Preliminary serology shows that at least one Canada goose (of 39 examined) was positive for exposure to toxoplasmosis, suggesting that migratory wildlife may be a source of introduction of the parasite into the eastern Canadian Arctic, as demonstrated in the central Canadian Arctic (Elmore et al. 2014). This may have important implications for both the ecology of parasite transmission and human health. Future lab analyses will reveal if the parasite is present in tissue consumed raw (such as gizzard). This information will help form the basis of assessing the risks of toxoplasmosis in country foods commonly consumed in Nunavik. It will also help to understand how the parasite is introduced and transmitted in Arctic ecosystems, important from both scientific, wildlife conservation, and public health perspectives.

2. Fox Genetics and Rabies

Previous work on specimens collected during the 2012-2013 outbreak allowed us to analyze the origin and spread of this recent epizootic in Labrador and northern Québec.

Previous mitochondrial DNA analysis identified one genetic cluster of arctic foxes, and three of red (coloured foxes), corresponding to the so-called Holarctic, Nearctic, and Widespread clades (Aubry et al. 2009). This result suggests that arctic foxes move greater distances than coloured foxes, thus could be more effective disease spreaders. The STRUCTURE analysis of the microsatellite data supports the broad findings of the mitochondrial DNA data. However, other types of analysis such as

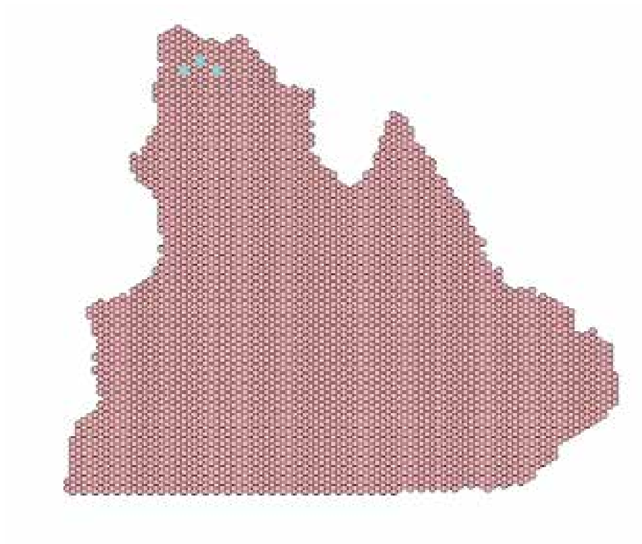

Figure 8. Landscape of hexagonal cells structuring population and epidemiological processes in the Ontario Rabies Model. The landscape extent was designed to match Nunavik. The turquoise cells show outbreak locations of arctic fox rabies used in preliminary simulations.

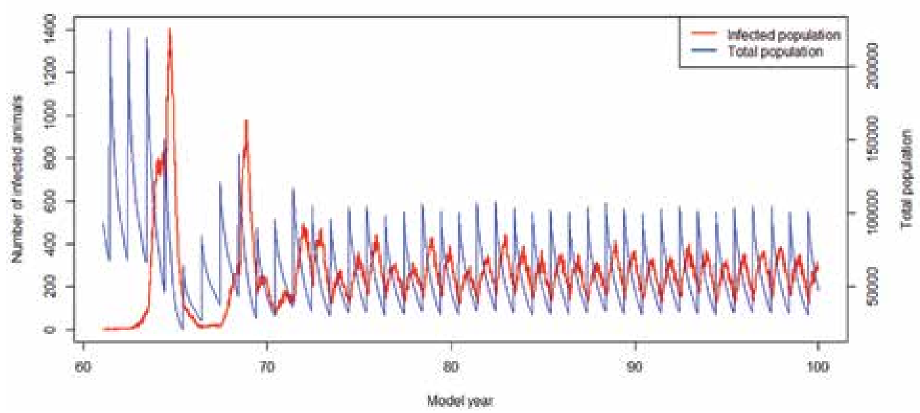

Figure 9. Example output from an arctic fox rabies simulation using the Ontario Rabies Model.

factorial correspondence analysis and pairwise FSTs suggest greater differentiation among locations in both Labrador (coloured foxes) and Nunavut (arctic foxes). Detecting a more complex population structure with microsatellites than mtDNA is consistent with microsatellites providing higher resolution in space-time signatures. Also, as mtDNA is maternally inherited, the inclusion of the microsatellite data should shed light on sex-specific behaviour and resulting gene flow due to the movement patterns of males.

Additional and more detailed genetic analyses including a greater number of genetic loci (eg. single nucleotide polymorphisms) and more in-depth viral sequencing to provide a finer scale resolution of host and virus genetic structure are underway. This approach, combined with greater fox sampling (e.g. greater geographical coverage of Nunavik, James Bay, and Labrador, larger samples sizes, longer time-period) will allow us to better identify genetic clusters and population boundaries, as well as local dispersal corridors and natural barriers to movement. The implications of detected landscape features affecting gene flow, and hence, fox movement patterns on rabies spread and public health risk will be tested with the arctic fox rabies simulation model. For example, the model can be used to a) test the strength of landscape features to facilitate or impede disease spread, b) spread probability routes can be estimated, and c) effectiveness of surveillance and control strategies can be evaluated. By integrating project knowledge gains from landscape genetics, ecology and epidemiology into mathematical modelling, we remain on-track to producing useful simulation tools for guiding surveillance and control activities and informing public health risk.

3. People, dogs and wildlife

Preliminary results of the survey analysis showed that a good level of rabies vaccine coverage is observed (>75%). This may be partly explained by a previous outbreak of distemper in dogs in Kuujjuaq during the spring 2015 which led several dog owners to vaccinate their dog before the survey. Preliminary comparative analysis of the survey results between JBNQA beneficiaries and other Kuujjuaq residents showed several significant differences between habits and perceptions of dogs and their importance for the Inuit culture. This may have an impact on risk exposure related to dogs and on the acceptability of potential interventions to mitigate those risks between different subgroups of Kuujjuaq residents. Additional analyses will include statistical tests to formally assess the differences observed between JBNQA beneficiaries and non-beneficiaries, as well as qualitative analyses of open questions.

4. Climate and disease modelling

Non-spatial classical epidemiological models that assume homogeneous mixing of hosts have been invaluable for understanding and managing rabies dynamics in European red fox populations (Anderson et al. 1981). These models, however, fail to capture the complex dynamics of arctic fox rabies. This shortcoming underlies the need to build increased realism of fox ecology within the Arctic disease-host ecosystem into modelling applications. The ongoing developments of the spatially explicit Ontario Rabies Model into the Arctic Rabies Model, will allow us to explore the importance of geography on regional rabies dynamics, and specifically the importance of long-distance movements of arctic foxes on rabies persistence. Preliminary simulation results are encouraging in that just by having a spatial context that allows for heterogeneous mixing of hosts, allows rabies persistence in low-density fox populations even in the absence of long-distance movements. In effect, spatial models enable simulation of meta-population dynamics. The virus can persist in asynchronous subpopulations, so that periodic disease spillover among the subpopulations keeps the disease persisting in the overall population. We believe this process may be critical to arctic fox rabies persistence in the low density north host populations, and is likely the mechanism of disease reemergence into southern Canada.

CONCLUSION

In Year 1, our team made significant progress toward each of our project objectives by establishing a wildlife disease monitoring network, building trust and collaborations with partner communities and aligning research goals with local needs through community consultation, and gathering the necessary information and refining tools to carry out climate-coupled disease modelling.

Detecting and characterizing zoonotic diseases in wildlife

Frequent field trips and sustained community dialogue in Year 1 made it possible to quickly establish a network of participating communities for toxoplasma, trichinella and rabies virus monitoring. Samples collected from Year 1 are being processed while Year 2 collection is under way in an extended network of communities, covering an even greater area than planned at the outset of the project. Early sample collection allowed us to test and refine laboratory techniques and protocols, allowing efficient treatment of the 150% increase in collections planned for Year 2. Preliminary results confirm that the disease monitoring efforts of our project will provide a unique multi-year baseline for human exposure to wildlife diseases in the Eastern Subarctic.

Assessing contact rates and potential routes of exposure between people and wildlife at the community level

A strong engagement by the community of Kuujjuaq to partner with our team to tackle health issues related to dogs, including zoonotic diseases such as rabies, made it possible to adapt research goals and objectives to meet local needs and concerns. This process was greatly facilitated by repeated visits to the community and active engagement of community members through meetings, interviews and the provision of animal health clinics by team members. Our survey of Kuujjuaq dog-owners provided important information on potential differences in zoonotic disease risk within the community, and community knowledge about the frequency of interactions with different wildlife species. These data begin to describe potential routes and risks of wildlife disease transmission in a model northern community, results that will guide field work in this area in Year 2.

Models of human exposure to wildlife disease and future disease risk under changing climate

The availability of historical data on rabies allowed us to carry out statistical analyses and preliminary modelling in Year 1 that will allow model validation to take place as field data become available in Years 2 and 3. These activities also lead to the preparation of five manuscripts (two submitted and three in preparation) that document each stage of the modelling process. Preliminary simulations suggest the feasibility and value of investing in a spatial simulation approach to understanding rabies epidemiology in the Arctic, and pave the way for models of toxoplasma and *Trichinella* spatial dynamics that will be developed in Year 2.

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Ecosystem Approaches to Northern Health

Project Leader

Mélanie Lemire (Université Laval)

Collaborators

Ellen Avard (Makivik Corporation)
Michael Barrett (Kativik Regional Government)
Minnie Grey (Makivik Corporation)
Nancy Gros-Louis (First Nation of Quebec and Labrador Health and Social Services Commission)
Michael Kwan (Makivik Corporation)
Elena Labranche (Nunavik Regional Board of Health and Social Services)

HQP

Julie Ducrocq, Doctoral Student (Université Laval)
Ecology of Besnoitia tarandi in barren-ground caribou (Rangifer tarandus)
François Beaubien, Masters Student (Université Laval)
Francis Dufour, Masters Student (Université Laval)
Joannie Gray-Roussel, Masters Student (Université Laval)
Emad Tahir, Masters Student (Université Laval)
Abdullah Al Maruf, Post-Doctoral Fellow (Université Laval)
Joao Guedes de Oliveira, Technical Staff (Université Laval)
Annie Turgeon, Technical Staff (Centre de Recherche du Centre hospitalier de l'Université Laval)
Julien Vachon, Technical Staff (Université Laval)
Anne Corminboeuf, Undergraduate Student (Université du Québec à Rimouski)
Vincent Mireault, Undergraduate Student (Université Laval)

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 forms 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

- The Nasivvik research chair was officially created in January 2016 and launched June 16th 2016 during the Northern Health Forum at Université Laval.
- The First Nation of Quebec and Labrador Health and Social Services Commission is now part of the Nasivvik chair partners and Minnie Grey agreed to join the Nasivvik Chair steering committee.
- The Nasivvik chair team members are actually involved in more than ten participatory, interdisciplinary and intersectoral projects. The team involves two undergraduate students, four master students, one PhD student, one postdoctoral researcher, two research assistant, one chair coordinator and the titular chair.
- Two high-impact manuscripts were published in 2016 and several community-based activities took place between March and June 2016.

MISSION & OBJECTIVES

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.

This research chair focuses on these six main objectives:

1. Contribute to biomonitoring of environmental contaminants in local foods and northern populations;
2. Study the effects of contaminants on human health and the effects of contaminant/nutrient interactions in foods and on health;
3. Study the prevalence and incidence of zoonoses and other infectious agents, and their environmental and social determinants;
4. Study the effects of local and regional development on the chemical and microbiological quality of drinking water and local foods, and their impact on the health of northern populations and workers;
5. Study the impact of climate and ecosystem changes on local food systems (quality, availability, access, use, sustainability) and on northern health; and
6. Mobilize knowledge into action by:
   a. Integrating, sharing, and discussing research outcomes with co-investigators, decision makers, key actors, and communities in northern regions;
   b. Developing, implementing, and evaluating projects, particularly with youth and in close partnership with regional and local partners;
   c. Strengthening the research capacity of Indigenous youth and the capacity of practitioners in the fields of health, social services, the environment, and education;
   d. Contributing to regional and national risk assessment initiatives and implementing public health policies; and
   e. Taking part in national and international councils and expert panels on Indigenous health and environmental contaminants.

INTRODUCTION

Northern ecosystems are undergoing rapid changes and Indigenous peoples, who cultivate strong ties with their environment, are particularly vulnerable to these changes. Université Laval's research in the Arctic played a key role in negotiations leading to the Stockholm Convention on Persistent Organic Pollutants (POPs) and, more recently, the Minamata Convention on Mercury. While POPs are declining, mercury is still a topical issue in the North. Furthermore, many new chemicals brought to market each year subsequently end up at the poles, with unknown impacts on the health of its inhabitants. Natural resources exploitation and climate change are also putting increasing pressure on northern environments and affecting the health of northern populations in many ways, including through the contamination of locally sourced foods and food insecurity, an issue throughout the North.

Indigenous knowledge highlights the importance of local foods for health and well-being. Modern science supports this knowledge: foods from the ocean are exceptionally rich in essential nutrients such as omega-3 fatty acids and selenium. Wild berries and other northern plants are also a key source of polyphenols. These foods offer unique potential to bring together a range of knowledge aimed at preventing chronic illness and the effects of environmental contaminants on health.

ACTIVITIES

Research activities of the chair

The chair's objectives are addressed in several ongoing and future research projects:

1. Designing and implementing the Nunavik Health Survey Qanuilirpitaa 2017, ArcticNet, 2015-2018, 546K, PI: Pierre Ayotte; Mélanie Lemire; Benoît Lévesque; Gina Muckle; Michel Lucas; Mylène Riva

- M. Lemire is one of the four co-PI of the Physical Health component of Qanuilirpitaa 2017. M. Lemire is the leader of the oral health component and the co-leader of the contaminant, zoonosis, drinking water, *Helicobacter pilori* and gastroenteritis components. For this year, we are focussing on research methods and questionnaires design and piloting. Consultation activities with Inuit colleagues took place in March 2016 (see Appendix D). The survey pilot will be conducted in October 2016 in Inukjuak and a pilot of the oral health exam protocol may be realised in Quebec city this summer and in Kuujjuaq in collaboration with the dentist Dr Aurélie Paul in Kuujjuaq during fall.
- Chair students in this project (funded by ArcticNet): Julie Ducrocq (PhD zoonosis and health), Vincent Mireault (MD dentistry, summer intern).
- A small study in Alaska suggests that Inuit can naturally develop immunity against rabies (Orr et al, 1988). This summer, for her PhD and in preparation for Qanuilirpitaa 2017, J. Ducrocq will conduct rabies antibodies measurements in a sub-sample of archived serum of participants of the 2004 Qanuippittaa study. The sub-sample criteria are participants frequently hunting for game meat and manipulating carcasses that were never vaccinated against rabies.
- We received a 1M$ grant from Kativik School Board to involve young Inuit as trainees in the preparation and realisation of Qanuilirpitaa Survey onboard the CCGS *Admunsen*.
- This fall, we are planning to apply to a CFI Fonds JR Evans (300K) and to CIHR to get extra funding for physical and oral health part of the Qanuilirpitaa Survey, which actual budget is of 10M$.

2. Supporting understanding, policy and action for food security in Nunavik and Nunatsiavut, ArcticNet, 2015-2018, 333K, PI : Chris Furgal, Co-Investigators: Michel Lucas, Cedric Juillet, Mélanie Lemire, Christopher Fletcher

- M. Lemire participated in the discussions and questionnaires design of the Food Frequency Questionnaire, traditional activities and country food risk communication components of Qanuilirpitaa.

3. 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, Health Canada, 2014-2016, 612K, PI: Mélanie Lemire, Co-Investigators: Pierre Ayotte; Gina Muckle; Michel Lucas; Mylène Riva, Collaborators: Nancy Gros-Louis (FNQLHSSC), Suzanne Bruneau (INSPQ)

- M. Lemire leads the entire project. We are currently in the phase of analysing data and returning study results to the parents of the participants and community partners (April – June 2016). Almost all parents (>75%) were met individually, which set the place to one-to-one discussions based on their children's results. Study findings were also shared with health directors, several community practitioners, school directors and teachers. The First Nations involved in the project are in Abitibi-Témiscamingue region (below 49th parallel) and the Lower North Shore region (Nutashkuan,Unamen shipu). The final report will be provided to communities and Health Canada later this year.

- A factsheet was developed to inform community members on how to avoid lead from ammunitions (see Appendix E). This factsheet was shared by Health Canada to several First Nation communities across the country. Cree and Inuit boards of health also adopted and improved the document for their regions.
- Chair MSc students in this project (not funded by ArcticNet): Joannie Gray-Roussel (food security determinants) and Emad Tahir (anemia and environmental health issues).
- This is a pilot of a pan-Canadian study on First Nation Youth, Environment and Health Study, which M.Lemire will probably co-lead with Malek Batal at Université de Montreal (Co-leader of First Nation Food Nutrition Environment Study (FNFNES)), starting in 2017.

4. Do country food nutrients protect against mercury toxicity and cardiometabolic diseases? Integrating data from cutting-edge science and mobilizing knowledge towards Nunavimmiut health, Northern Contaminants Program, 2014-2017 (Year 3), 258K, PI: Pierre Ayotte, Co-Investigators: Mélanie Lemire, Guillaume Massé, Michel Lucas, Maruf Abdullah Al (postdoctoral researcher in my team), Ellen Avard, Michael Kwan.

- M. Lemire co-leads this with Pierre Ayotte. One manuscript was recently accepted for publication in Environment International (see publication list). Research preliminary findings were presented to Nunavik colleagues and community members in March 2016 (see Appendix F). A summary of the findings is presented in the result section.
- Chair students in this project (partly funded with ArcticNet): Francis Dufour (MSc selenoneine in country foods), Anne Corminboeuf (BSc biology summer intern on nutrients in fish species).
- These findings will be critical for the finalisation of the Selenium risk assessment initiative on-going at Health Canada (http://gazette.gc.ca/rp-pr/p1/2015/2015-07-18/html/notice-avis-eng.php#ne2; http://chemicalsubstanceschimiques.gc.ca/group/selenium-eng.php).

5. Is high Se intake from a marine diet during pregnancy and childhood neurotoxic or mitigating the adverse effects of MeHg exposure on child development? Northern Contaminants Program, 2015-2016, 122K, PI: Mélanie Lemire, Gina Muckle, Co-Investigators: Pierre Ayotte, Dave Saint-Amour.

- We are currently finalizing data analysis. Two manuscripts are in preparation. Selenoneine analysis in archived blood samples from the Nunavik Child Cohort Study are on-going. We will share the data with our Nunavik partners in the communities in the months to come. A summary of the findings is presented in the Results section.
- These findings will be critical for the finalisation of the Selenium risk assessment initiative on-going at Health Canada (http://gazette.gc.ca/rp-pr/p1/2015/2015-07-18/html/notice-avis-eng.php#ne2; http://chemicalsubstanceschimiques.gc.ca/group/selenium-eng.php).

6. Exposure to food chain contaminants in Nunavik: evaluating spatial and time trends among pregnant women and implementing effective health communication for healthy pregnancies and children, Northern Contaminants Program, 2016-2019 (Year 1 of 3), 360K, PI: Mélanie Lemire, Pierre Ayotte, Chris Furgal, Catherine Pirkle, Co-Investigators: Gina Muckle, Amanda Boyd, Collaborators: Sylvie Ricard, Marie-Josée Gauthier, Caroline d'Astous and Carole Beaulne (NRBHSS), Ellen Avard and Michael Kwan (NRC), Suzanne Côté and Therese Adamou (CHU de Quebec).

- Our first team meeting was held June 15th during the Nunavik Nutrition and Health Committee in Quebec City. Nunavik physicians, midwife and nurses will also be directly involved in the project. The questionnaires and consent form are currently in preparation for ethical approval by the end of the summer.
- Pregnant women recruitment will take place in all Nunavik communities, starting next October 2016.
- This project aims at continuing Dr. Éric Dewailly's biomonitoring activities in Nunavik and was based on our ground-breaking work to be published in CMAJ (see publication list). Findings of Year 1 will be used to further improve our communication on country food recommendations and healthy pregnancies and children for health practitioners, pregnant women and their partners.

7. Genetic polymorphisms to improve interpretation of contaminant exposure and risk in Inuit, Northern Contaminants Program, 2014-2017 (Year 3), 46K, PI: Nil Basu, Pierre Ayotte, Co-PI: Laurie Chan, Robert Hegele, Mélanie Lemire.

- Sample analysis is on-going. Data sharing and manuscripts are in preparation. A summary of the findings is presented in the Results section.

8. Quantifying the effect of transient and permanent dietary transitions in the North on human exposure to persistent organic pollutants and mercury, Northern Contaminants Program, 2016-2017, 34K, PI: Frank Wania, Meredith Current, Co-Investigators: James Armitage, Laurie Chan, Mélanie Lemire.

- The project is starting this summer.

9. Uniting Traditional Ways and Science around medicinal plants/foods for the better prevention and management of Type 2 Diabetes in Canadian First Nations, CIHR, 2016-2018, 200K, PI: Haddad P; Co-investigators: Cuerrier A, Foster B, Harris C, Lemire M, Arnason JT, Leigh J, Imbeault P, Herrmann TM, Co-knowledge Users: Isheroff A, Guanish G; Blacksmith J, Mitchell J, Simeon J, Bearskin L, Brascoupe S, Larouche V.

- The project will be realised in several First Nation communities including Kawawachikamach (above the 49th parallel). We are currently in the phase of consulting with community members to further develop the community intervention projects.

10. Inuit knowledge and food quality/security component of the GreenEdge project, PI: Marcel Babin, Co-Investigators: Michelle Terrien, Frédéric Laugrand, Christopher Fletcher, Mélanie Lemire, Guillaume Massé, Frédéric Maps.

- This project aims at understanding the dynamics of the phytoplankton spring bloom and determining its role in the Arctic Ocean of tomorrow, including for human populations. The GreenEdge research project is pan-Arctic and involves researchers from more 23 research centres in Canada, France and Greenland. Our last international meeting was at INALCO in Paris, in November 2015.
- We are currently consulting with our Inuit partners in Qikiqtarjuaq to develop this component of the project. Field research to document Inuit knowledge with respect to hunting and ice-conditions was conducted in May 2016.
- A new postdoctoral researcher (Tiffannie-Anne Kenny) will likely be involved in this project in Sept 2016.

Several research proposals were submitted in June 2016:

11. Health, environment, climate change, and indigenous peoples challenges in the Arctic. A collaboration in higher health education and research between UiT The Arctic University of Norway, and Laval University, Quebec, Canada, Norwegian Centre for International Cooperation in Education, 2017-2020, 1 999 944 NOK, PI: Jon Odland, Co-Investigator: Mélanie Lemire, Shawn Donaldson and Jennifer Gibson (Health Canada). (Submitted June 1st 2016.)

12. Several LOI projects were submitted to Sentinelle Nord on June 1st 2016:

a. **BriGHT (Bridging Global change, Inuit Health and the Transforming Arctic Ocean)**, PI: Jean-Éric Tremblay, Mélanie Lemire, Co-Investigators: Dermot Antoniades, Philippe Archambault, Pierre Ayotte, Louis Bernatchez, Louis Fortier, Michael Kwan, Frédéric Laugrand, Johann Lavaud, François Laviolette, Michel Lucas, Frédéric Maps, Guillaume Massé, Gina Muckle.

b. **Microbiome: the missing link to understanding interactions between the Nunavik Inuit exposome and cardiometabolic disorders?** PI: Michel Lucas and Pierre Ayotte, Co-Investogators; Michel G Bergeron, Marie-Claude Vohl, Jean-Pierre Després, Claudia Gagnon, Fatiha Chandad, Mélanie Lemire, Gina Muckle, Richard E Bélanger.

c. **The gut microbiome: sentinel of the northern environment and Inuit mental health**, PI: Gina Muckle and Richard Bélanger, Co-Investigators: Michel G Bergeron, Chantal Mérette, Pierre Marquet, Marc Hébert, Pierre Ayotte, Mélanie Lemire, Michel Lucas, Marie-Claude Vohl.

d. **The use of a Neuropsychological Virtual Reality (VR) test battery based on Conviviality, Portability and Universality (Neuro-CPU) to detect cognitive changes related to living in the North,** PI: Phillip Kackson, Co-Investigators: Gima Muckle, Mélanie Lemire, Frédéric Laugrand, Carol Hudson, Denis Laurendeau, Bradford McFadyen, Pierre Marquet.

e. **Enabling tools for the monitoring of food quality in the Northern environment**, PI: Dominic Larivière and Jean Ruel, Co-Investigators: Pierre Ayotte, André Bégin-Drolet, Denis Boudreau, Jesse Greener, Mélanie Lemire, Gina Muckle.

13. LOI - Qikiqtarjuaq Research Centre, FCI, 5.2 M$, PI: Marcel Babin, Co-Investigators: Allard M, Archambault P, Domine F, Fortier L, Lemire M, Lovejoy C, Pienitz R, Tremblay JE, Warwick V. (Submitted June 23rd, 2016.)

14. The ECHO Network (Environment, Community, Health Observatory): Strengthening intersectoral capacity to understand and respond to health impacts of resource development, CIHR Environment and Health Signature, PI: Parkes M, Surette C, Harder, Takaro K, Hallstrom H, Gislason S, Stephen C, Co-Investigators: de Leeuw S, Lemire M, Moewaka Barnes, Greenwood M, Vaillancourt C, Saint-Charles J, Cole D, Brisbois B, Buse, Reschny, Woolard B, Bunch M, Horwitz. (Submitted June 30, 2016. (LOI accepted already).)

Outreach activities of the chair

- **Chair northern partners and steering committee**: In February 2016, Minnie Grey, director of the Nunavik Regional Board of Health and Social Services (NRBHSS), agreed to join the chair steering committee as an official representative of the northern partners of the Nasivvik chair. The Nasivvik chair is in continuity of the Nasivvik Centre for Inuit Health and Changing Environments, in which Minnie Grey played a key role since 2004. In April 2016, based on our successful collaboration with the First Nation Youth, Environment and Health Pilot Project (JES!-YEH!), the First Nation of Quebec and Labrador Health and Social Services Commission (FNQLHSSC) also agreed to join the partners of the chair. The Nunavik Nutrition and Health Committee (NNHC), which involves representatives of the NRBHSS, the Nunavik Research Centre (NRC) and the Kativik Regional Government (KRG), proposed that instead of joining the chair steering committee, the titular chairr could come present the progress of the chair activities and seek their guidance and input at each tri-annual meeting of the NNHC (November, February, June). A similar approach was chosen for the FNQLHSSC partnership. The next steering committee meeting is planned for September 2016. Meanwhile, the research chair's results, outcomes and training capacities will be documented and periodically presented to the steering committee members. The research chair coordinator will inform the steering committee of the activities and progress of the research chair.

- **Promotional documents**: A three language-factsheet (English, French, Inuktitut) presenting the research chair mission, activities and partners was developed between January and June 2016 (see Appendix A). A bilingual website was also developed and will be launched shortly: www.nasivvik.chaire.ulaval.ca. The website includes a description of on-going primary research projects at the Nasivvik Chair, the Éric Dewailly Nasivvik Chair Award (see below), the research team and most recent activities.
- **Launch of the chair**: The Nasivvik chair was officially launched June 16th during the Northern Health Forum at Université Laval. The ceremony was animated by the Medecine Faculty dean, Dr. Rayland Bergeron. Dr. Éric Beauce, the vice-doyen of Ulaval, Dr Ellen Avard, director of the NRC (in replacement of Minnie Grey), Martin Fortier, former executive director of ArcticNet, and Sarah Kalhok Bourque, director of the Northern Contaminants Program of the Indigenous Affairs and North Canada, were invited to express their support for the Nasivvik research chair and his titular expertise in the field. M. Lemire also presented the chair partners, mission, objectives and the recipient of the 2006 Éric Dewailly Nasivvik Chair Award (see below and Appendix B). Several interviews were given: Le Fil de l'Université Laval and Le Soleil, NunatsiaqNews, Radio-Canada Boréal, Radio-Canada Côte-Nord, and Bien dans son assiette (Radio-Canada Première). A vibrant tribute was given to Dr. Éric Dewailly, which was behind this research chair project and passed away two years ago. (www.lefil.ulaval.ca/service-communautes-nordiques/; www.fmed.ulaval.ca/la-faculte-et-son-reseau/a-surveiller/nouvelles/detail-dune-nouvelle/nouvelle-chaire-nasivvik/; www.pressreader.com/canada/le-soleil/20160618/283948881898707; www.nunatsiaqonline.ca/stories/article/65674new_research_position_to_focus_on_arctic_contaminants_human_health/; www.ici.radio-canada.ca/emissions/bien_dans_son_assiette/2015-2016/archives.asp?date=2016-06-17)
- **Éric-Dewailly Award for community-based project in indigenous context**: The Fond en santé des populations Éric-Dewailly (4433)[1], hosted at the Fondation de l'Université Laval, was used to fund an annual Nasivvik Chair Award untitled: *Bourse Éric Dewailly pour des projets communautaires en santé autochtone*[2]. This award of 5 000 CAN$ (non-renewable) aims to encourage students to share and discuss the results of their research in indigenous communities involved in their projects. This scholarship also offers the possibility of developing a community project for health prevention activities and to promote environments that foster health and well-being. This year, the 2016 award recipient was Therese Adamou for a project related to her PhD findings untitled: "Bilan sur l'évolution des femmes enceintes au mercure, au plomb et aux BPC au Nunavik".
- **Invited talks and Publications**: M. Lemire was invited to present our latest research findings on selenium and mercury interactions during the Colloquim "Neuropsychotoxicologie environnementale: un mariage interdisciplinaire heureux" at the Association francophone pour le savoir (ACFAS) May 10th, 2016 (see publication list). In addition, M. Lemire was invited to present a complete overview of the Nasivvik chair research projects and activities during the Northern Health Forum at Université

[1] https://commerceweb.ulaval.ca/shopping/ful/product/4433/Index.view?pnkey=538116d393a60b7bb89995cb9dda7cb475ccca75

[2] https://repertoire.bbaf.ulaval.ca/bourse/25194/bourse-eric-dewailly-pour-les-projets-communautaires-en-sante-autochtone-ete-2016?cycle=3&faculty=49&session=&programs[]=378&start-search=Chercher&idul=&showOnlyAlwaysAvailable=false

Laval June 16th, 2016 (see Appendix C). Since January 2016, two manuscripts were accepted for publication in two prestigious journals, the Canadian Medical Association Journal (CMAJ) and Environment International (2014/2015 IF 5.96 and 5.93 respectively) (see publication list). Our manuscript in CMAJ, reviewing the state of the evidence and dietary recommendations on how to manage mercury exposure in Northern Canadian communities, will reach a great audience of health professionals across the country and has been selected for a new release when the manuscript will be published next July.

- **Community-based activities**: P. Ayotte, B. Lévesque and M. Lemire went to Kuujjuaq and Puvirnituq in March 2016. The objectives of these travels were to present and discuss the physical health components of Qanuilirpitaa (oral health, cardiometabolic health, gastroenteritis and drinking water, zoonotic diseases, genetic, etc.) and to share our latest research findings with respect to selenium and selenoneine, a new form of selenium identified both in Inuit blood and in beluga mattaaq, the primary dietary source of selenium (see Appendix D). During these meetings we met NRBHSS and KRG colleagues, midwives, nurses, physicians, and Tulattavik and Inuulitsivik hospital directors. We also met Puvirnituq mayor, municipal counsellors, hunters and water plant supervisor. Their interest for the Qanuilirpitaa survey was noteworthy – several positive and constructive feedbacks were provided. Our findings on selenoneine generated a great enthusiasm from hunters and the mayor. As one of the young hunters said "We already know since several years that mattaaq is good for us! This is very good news for Nunavimmiut." M. Lemire and her staff visited the four communities involved in the JES!-YEH! project to bring back results to study participants and their parents. Almost 75% of the parents who participated in the study were met, a great success. This approach ended up being much more effective for knowledge sharing and discussion than more traditional community meetings, in which attendance is generally not that high, despite great interest in the project. We also met with chiefs and several health and education practitioners, who were very welcoming and interested in the study's findings.
- **Student fellowships and recruitment:** Thanks to the Nasivvik chair, several students are recipient of fellowships from multiple disciplines: two summer interns (undergraduate programs in Biology and Dentistry), four MSc students (Community Health, Epidemiology and Biology), one PhD student (Epidemiology) and one postdoctoral fellow (Toxicology and Epidemiology). Once our website is online, we hope to recruit more brilliant and dynamic students to get involved in the research chair activities in the years to come. M. Lemire will also start teaching the introductory course in environmental health at Université Laval this fall, a great opportunity to recruit students. M. Lemire is also part of a new CHIR proposal (led by Chantelle Richmond, Western University), which aims at reinforcing the number and success of First Nations students in our academic institutions, who eventually go on to get research positions to truly influence and bring forward the Indigenous research agenda and methodologies.

RESULTS

Some key findings from three of our Northern Contaminants Program projects in 2015-2016:

4. Do country food nutrients protect against mercury toxicity and cardiometabolic diseases? Integrating data from cutting-edge science and mobilizing knowledge towards Nunavimmiut health, 2015-2016 (Year 2).

- Selenoneine, an organic form of selenium, represents more than 50% of selenium in beluga mattaaq samples from Nunavik and Nunavut.
- Selenoneine was identified as a major Se compound in red blood cells of Nunavimmiut.
- Selenoneine may enhance methylmercury demethylation and decrease its distribution to target organs.
- Whether or not selenoneine protects against methylmercury toxicity is currently being examined.

5. Is high Se intake from marine diet during pregnancy and childhood neurotoxic or mitigating the adverse effects of MeHg exposure on child development? Northern Contaminants Program, 2015-2016.

- This study aimed at re-analysing the 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.
- Blood selenoneine analysis in archived NCDS blood samples were added to the study design and are underway.
- All study results will be available, presented to the Nunavik population and published in fall 2016 – winter 2017.

7. Genetic polymorphisms to improve interpretation of contaminant exposure and risk in Inuit, 2015-2016 (Year 2).

- 146 genetic polymorphisms were characterized from some members of the Inuvialuit community who participated in the 2007-2008 International Polar Year Inuit Health Survey.
- These polymorphisms hail from biological pathways associated with, for example, the transport and metabolism of contaminants and cardiovascular health.
- Composition of many of the genetic polymorphisms were different when compared against other populations such as Caucasians and Asians.
- Some genes are associated with changes in blood levels of mercury, cadmium, lead, DDE, PCB153, and fatty acids DHA and EPA.
- Next steps will be to repeat the gene-environment study with already collected samples and information from the 2004 Qanuippitaa Survey.

CONCLUSION

The Nasivvik chair is a unique opportunity to consolidate several research projects on-going in environmental and indigenous health at Université Laval. It also creates a great environment for student training and for gaining the skills and experience for cutting-egde science and in community-based research. The next year will be critical for recruiting more graduate students and acquiring more funds to further develop Objectives 4 to 6 of the research chair.

ACKNOWLEDGEMENTS

Our partnership with northern institutions is crucial for meaningful and high-impact science at local, regional, federal and international scales. Their guidance and support is of inestimable value. Moreover, all these projects would never be possible without community members participation in our projects, from 3 years old to elders' age! Their suggestions, supports, storytelling and invitations to community activities are always a unique moment of exchange and to foster our knowledge of their culture, their health and their environment. It's also great to get their input for better research. Nakurmikarialuk! Megtweetch!

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Appendix A

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NASIVVIK RESEARCH CHAIR IN ECOSYSTEM APPROACHES TO NORTHERN HEALTH

Faculty of Medicine

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 and land to sustain health and wellbeing.

CHAIR CREATION: January 2016

This research chair is part of Université Laval's Program for the Advancement of Innovation, Research, and Education (PAIRE), which aims to create a stimulating research environment for innovation, ingenuity, and creativity on the part of the university's research professors.

BACKGROUND

Northern ecosystems are undergoing rapid changes and Indigenous peoples, who cultivate strong ties with their environment, are particularly vulnerable to these changes. Université Laval's research in the Arctic played a key role in negotiations leading to the Stockholm Convention on Persistent Organic Pollutants (POPs) and, more recently, the Minamata Convention on Mercury. While POPs are declining, mercury is still a topical issue in the North. Furthermore, many new chemicals brought to market each year subsequently end up at the poles, with unknown impacts on the health of its inhabitants. Natural resources exploitation and climate change are also putting increasing pressure on northern environments and affecting the health of northern populations in many ways, including through the contamination of locally sourced foods and food insecurity, an issue throughout the North.

Indigenous knowledge highlights the importance of local foods for health and well-being. Modern science supports this knowledge: foods from the ocean are exceptionally rich in essential nutrients such as omega-3 fatty acids and selenium. Wild berries and other northern plants are also a key source of polyphenols. These foods offer unique potential to bring together a range of knowledge aimed at preventing chronic illness and the effects of environmental contaminants on health.

CHAIRHOLDER

Mélanie Lemire is an assistant professor in the Department of Social and Preventive Medicine and a researcher at the Axe Santé des populations et pratiques optimales en santé of the Centre de recherche du CHU de Québec. She is a co-investigator at the Nasivvik Centre for Inuit Health and Changing Environments, whose mission is "Moving from health research on Inuit, to research with Inuit, and ultimately to research by Inuit." Ms. Lemire is also a co-investigator with the Canadian Community of Practice in Ecosystem Approaches to Health (CoPEH-Canada) and a member of Centre de recherche interdisciplinaire sur le bien-être, la santé, la société et l'environnement (CINBIOSE) based at Université du Québec à Montréal (UQAM).

She won the esteemed Banting-IRSC scholarship for her postdoctoral work on environmental epidemiology at Université Laval. She holds a master's degree and a PhD in environmental sciences from UQAM, for which she received the Governor General's Academic Medal and an Exceptional Early Career in EcoHealth Award.

UNIVERSITÉ LAVAL

CHAIRE DE RECHERCHE NASIVVIK EN APPROCHES ÉCOSYSTÉMIQUES DE LA SANTÉ NORDIQUE

Faculté de médecine

MISSION

Développer des projets de recherche et d'intervention interdisciplinaires, en étroit partenariat avec les peuples autochtones, pour innover en recherche et comprendre les effets complexes des changements environnementaux sur la santé, pour agir en prévention et pour promouvoir les écosystèmes nordiques avant tout comme des milieux de vie pour soutenir la santé et le bien-être.

CRÉATION DE LA CHAIRE : Janvier 2016

Cette chaire de recherche s'inscrit dans le Programme pour l'avancement de l'innovation, de la recherche et de l'enseignement (PAIRE) de l'Université Laval, lequel vise à instaurer un environnement de recherche stimulant l'innovation, l'inventivité et la créativité chez les professeurs.

CONTEXTE

Les écosystèmes nordiques se transforment rapidement, et les autochtones, qui cultivent un lien étroit avec leur environnement, sont particulièrement vulnérables à ces changements. Les recherches de l'Université Laval en Arctique ont joué un rôle décisif dans les négociations qui ont mené à la Convention de Stockholm sur les polluants organiques persistants (POP) et, plus récemment, à celle de Minamata sur le mercure. Alors que les POP sont en déclin, le mercure demeure un enjeu d'actualité dans le Nord. De plus, chaque année, plusieurs substances chimiques sont mises sur le marché et subséquemment retrouvées aux pôles, avec des effets méconnus pour la santé de ses habitants. L'exploitation des ressources naturelles et les changements climatiques exercent également des pressions grandissantes sur les milieux nordiques et affectent la santé de leurs habitants à de nombreux égards, notamment par la contamination des aliments issus de l'environnement local et quant à l'insécurité alimentaire, qui est omniprésente dans le Nord.

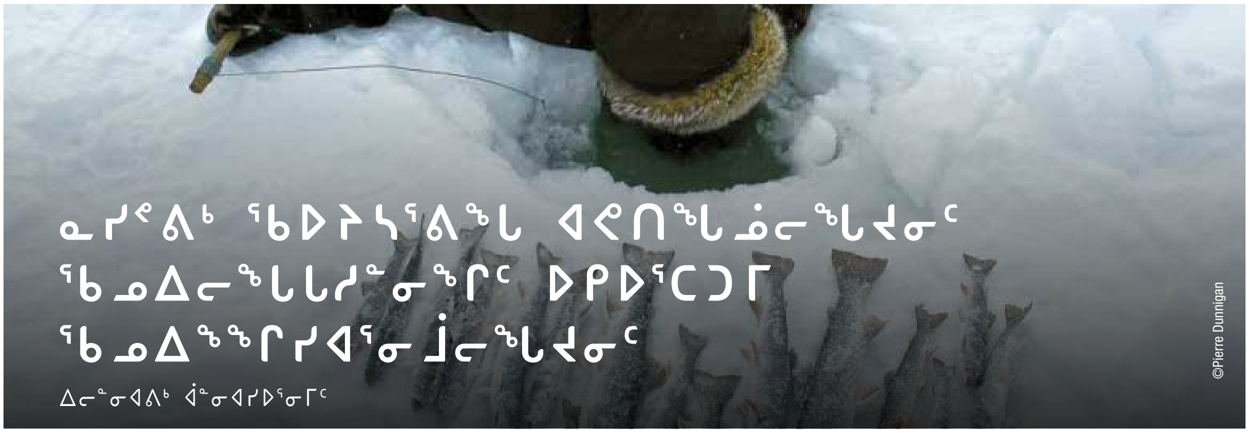
Le savoir autochtone met en évidence l'importance des aliments locaux pour la santé et le bien-être. La science moderne soutient ces connaissances; les aliments issus de la mer sont exceptionnellement riches en nutriments essentiels tels que les oméga-3 et le sélénium. Les baies sauvages et autres plantes nordiques sont aussi une source importante de polyphénols. Ces aliments offrent un potentiel unique pour rallier différents savoirs visant la prévention des maladies chroniques et des effets des contaminants environnementaux sur la santé.

TITULAIRE

Mélanie Lemire est professeure adjointe au Département de médecine sociale et préventive et chercheuse à l'Axe Santé des populations et pratiques optimales en santé du Centre de recherche du CHU de Québec. Elle fait partie des cochercheurs du Centre Nasivvik pour la santé des Inuits et les changements environnementaux qui a pour mission de « passer de la recherche en santé des populations inuites à la recherche avec les Inuits et, finalement, à la recherche par les Inuits. » Elle est également cochercheuse au sein de la communauté de pratique canadienne en approches écosystémiques de la santé (CoPEH-Canada) et membre du Centre de recherche interdisciplinaire sur le bien-être, la santé, la société et l'environnement (CINBIOSE), basé à l'Université du Québec à Montréal (UQAM).

Elle a remporté la prestigieuse bourse postdoctorale Banting-IRSC pour son postdoctorat en épidémiologie environnementale à l'Université Laval. Elle est titulaire d'une maîtrise et d'un doctorat en sciences de l'environnement de l'UQAM, pour lequel elle a reçu la Médaille académique du Gouverneur général et le prix Early Exceptional Career in Ecohealth.

UNIVERSITÉ LAVAL



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ᑖᓐᓇ ᖃᐅᔨᓴᕐᓂᖅ ᐃᓚᒌᔭᐅᔪᖅ ᓚᕝᕖᑦ ᐃᓕᓐᓂᐊᕖᕐᔪᐊᖅᑕᑦ ᐱᓇᓱᐊᕋᑦᓴᖅᑕᓄᑦ ᐊᓪᓗᓇᐊᖁᓪᓗᒍ ᓄᑖᒍᑦ, ᖃᐅᔨᓴᕐᓂᑯᑦ ᐊᒻᒪᓗᐃᓕᓐᓂᐊᓂᒃᑯᑦ, ᑐᕌᖓᖃᕐᓯᓂ ᓄᐃᑦᓯᓂᕐᒥᒃ ᐱᐅᓂᕐᓴᒥᒃᖃᐅᔨᓴᕐᓂᒥᒃᐊᕙᑎᑦᑎᓅᓕᖓᔪᓂᑦ ᓄᑖᑦᓯᐊᒥᒃ, ᐱᔪᓐᓇᓂᕐᒥᒃ ᐊᒻᒪᓗ ᓴᓇᑐᖅᓂᕐᒥᒃ ᐃᓚᒥᔭᐅᓂᖃᕐᓗᑎᑦ ᐃᓕᓐᓂᐊᑎᑦᓯᔩᑦ ᐊᐅᓚᑦᓯᔨᖏᓐᓄᑦ.

ᐃᓗᓕᖏᑦ

ᐅᑭᐅᖅᑕᑰᑉ ᐊᕙᑎᖓᓃᓕᖓᔪᑦ ᓯᑲᑦᑐᒥᒃ ᐊᓯᑦᔨᐸᓪᓕᐊᕗᑦ ᓄᓇᖃᖅᑳᖅᓯᒪᔪᐃᓪᓗ ᓄᓇᒥᓂᒃ ᐱᓯᒪᔪᓂᑦ ᐱᓲᑦ ᐊᑦᑕᓇᖅᑐᒦᑐᐃᓐᓇᕆᐊᖃᖅᑎᑕᐅᕗᑦ ᑖᒃᑯᓄᖓ ᐊᓯᑦᔨᓂᐅᔪᓄᑦ. ᖃᐅᔨᓴᓃᑦ ᓚᕝᕖᑦ ᐃᓕᓐᓂᐊᕖᕐᔪᐊᖓᓂ ᐅᑭᐅᖅᑕᑐᒥ ᐊᖏᖃᑎᒌᓐᓂᒥᒃ ᐱᓂᐊᕐᓂᖃᖅᑎᓯᔪᓐᓇᓂᕐᒥᒃ ᐊᖏᖃᑎᒌᓐᓂᐅᔪᓂᑦ ᓴᑦᑯᓪᓚ ᑲᑎᙵᓂᖅᔭᐊᖓᓂ ᖁᐱᕐᕈᐊᐱᐅᓯᕐᒨᓕᖓᔪᓂᒃ ᓯᒃᑯᓇᖅᑐᓂᒃ ᐊᓕᐅᓂᐊᕐᒥᒃ, ᒫᓐᓇᒃᑲᒥᐅᓂᖅᓴ ᒥᓇᒪᑕ ᑲᑎᙵᓂᖅᔭᐊᖓᓂ ᒧᒃᑯᓇᒧᓕᖓᔪᒥᒃ. ᖁᐱᕐᕈᐊᐱᕐᔨᑦ ᐃᑭᓕᐅᒥᓯᒪᓕᕋᔪᐊᕐᑎᓗᒥᑦ, ᒧᒃᑯᓇ ᓄᐃᑦᓚᓇᖅᑭᓐᓇᖅᑯᖅ ᐅᑭᐅᖅᑕᑐᒥ. ᐅᓇᓗᑦᑕᐅᖅ, ᐊᖅᑯᑕᒫᖅ, ᓄᐊᑕᕗᑦ ᐱᖅᑯᑎᑕᐅᓯᒪᔪᑦ ᓂᐅᕿᑕᐅᓰᕐᒍᕗᑦ ᑕᑯᑦᓴᐅᓯᑎᓗ, ᑕᒪᒥᓐᓂ ᓯᓚᕐᔪᐊᑉ ᑲᑦᓴᕐᓚᓂ ᐊᑖᓂᓗ, ᑐᑭᓯᒪᔭᐅᑦᔭᓚᑎᓗ ᓱᕐᕈᒍᑎᖅᑎᑦ ᐃᓄᓐᓂᒃ. ᐊᑐᓗᐊᕐᓃᑦ ᓄᓇᒥᑦᑐᓂᑦ ᓯᓚᐅᓪᓗ ᐊᓯᑦᔨᓂᖓ ᐅᖁᒣᓪᓚᐅᑎᑦᓯᕗᖅ ᐅᑭᐅᖅᑕᑰᑉ ᐊᕙᑎᖏᓐᓂᑦ ᓱᕐᕈᓯᓂᓗ ᐊᒥᓯᐃᓂᑦ ᐃᓗᓯᕐᓯᓯᐊᕐᓂᓄᓕᖓᔪᓂᑦ, ᐱᓗᐊᕐᑐᒥ ᓂᕿᑐᐃᓐᓇᓂᑦ ᓱᒃᑯᓇᕐᑐᑖᕋᓯᑎᒃ ᓯᐊᒻᒪᑉᓕᐊᕐᓇᓯᑎᓗ.

ᓄᓇᖃᖅᑳᖅᓯᒪᔪᐃᑦ ᖃᐅᔨᒪᔾᔪᑎᖏᑦ ᑕᑯᑦᓴᐅᑎᑦᓯᓯᐊᖁᑦ ᓂᕿᑐᐃᓐᓄᑦ ᐱᒪᓇᐅᕐᒥᐊᕐᓂᖏᓐᓂᑦ ᐃᓗᓯᕐᓯᓯᐊᕐᓂᒧᑦ ᖃᓄᐃᙱᓯᐊᕐᓂᒧᓪᓗ. ᓯᑯᐃᔭᓂᖅ ᓴᓪᒥᓯᐊᕐᖁᖅ ᓄᓇᖃᖅᑳᖅᓯᒪᔪᐃᑦ ᖃᐅᔨᒪᔭᕐᕆᓂᖅ; ᓂᕿᑦ ᑕᓇᐅᕐᒥᐅᕙᑦ ᐃᓗᓕᖃᕐᒪᑕ ᑎᒥᒻᒧᑦ ᐱᐅᔪᓂᒃ ᐅᕐᓯᓂᒃ (omega-3) ᐊᒻᒪᓗ ᑭᑭᐊᑦᓴᔮᑦ ᐱᐅᔪᐃᑦ (selenium). ᐸᐅᕐᖏᑦ ᐱᕈᖅᑐᐃᓗ ᐅᑭᐅᖅᑕᑐᒥ ᐃᓗᓕᑕᖃᕐᒥᓯᑎᒃ ᐳᓚᕙᓐᓂᒃ (polyphenol). ᑕᒪᒃᑯᐊ ᓂᕿᑦ ᐊᑑᑎᓕᒻᒪᓰᑦ ᑎᒥᒻᒧᑦ ᐊᕙᑎᑦᑎᓂ ᓱᒃᑯᓇᕐᑐᓂᒃ ᐱᓯᒪᔪᓂᒃ ᓱᕐᕈᑎᑦᓯᐅᑕᓗᓐᓇᑐᑦ ᑎᒦᑦ ᐋᓂᐊᖅᑎᓂᓚᕆᓪᓚᑦ ᖃᓄᐃᑦᑐᑐᐃᓐᓇᓂᑦ, ᓄᐃᑦᓯᓯᓂᓪᓗ ᑕᕐᕋᒥᐅᑦ ᐃᓅᓯᑦᑐᕐᑎᖅᑦᑕ ᐱᕈᕐᐸᓚᐊᑦᓯᐊᓂᖅᑎᓂᒃ ᓄᐃᑦᓯᒥᑦᓯᑎᓗ ᐃᓅᖅᑲᑎᒌᓂᑎᒍᑦ ᕿᓇᐅᔭᑎᒍᓪᓗ ᖃᓄᐃᙱᑎᐅᒍᓇᑐᓂᑦ.

ᐊᐅᓚᑦᓯᔨ

ᒥᓚᓂ ᓚᒦᕐ ᐃᓕᓐᓂᐊᑎᑦᓯᔨᐅᑉ ᐃᑲᔪᖅᑎᖓ ᐊᐅᓚᑦᓯᕕᑦ ᐃᓅᖅᑎᕆᑎᒍᑦ ᐊᑦᑕᓇᖅᑑᑦᑎᑦᓯᑦᑌᓚᒪᓂᕐᒧᑦ ᐋᓐᓂᐊᓯᐅᑎᓂᒃ ᐊᒻᒪᓗ ᖃᐅᔨᓴᕝᕕᑯᓂ ᐃᓚᐅᖃᑕᐅᒻᒥᔪᓂ ᐃᓗᓯᕐᓯᓯᐊᕐᓂᒃ ᓇᓴᐅᑦᓯᐊᑐᒥᒃ ᐱᐅᓂᖅ ᐃᓄᓐᓄᑦ ᐊᒻᒪᓗ ᐃᓗᓯᕐᓯᓯᐊᕐᓂᒃ ᐱᒥᐅᓴᐅᑏᑦ ᐋᓐᓂᐊᓂᓚᓈᓂᑦ ᐃᓕᓐᓂᐊᕖᕐᔪᐊᖅᑎᓐᖓᓂᒃ ᑯᐯᒃ.

ᐃᓚᐅᖅᑲᑕᐅᒻᒥᔪᓂ ᖃᐅᔨᓴᕐᑎᓂ ᓇᓯᕙᒃ ᐃᓄᓐᓄᑦ ᑐᑦᑕᕙᒃ ᐃᓗᓯᕐᓯᓯᐊᕐᓂᒃ ᐊᕙᑎᑦᑕ ᐊᓯᑦᔨᐸᓪᓕᐊᓂᖓᓄᑦ, ᑐᕌᖅᑲᖅᓯᓂ ᐱᒥᐊᕐᑎᓯᓂᕐᒥᒃ ᐃᓗᓯᕐᓯᓯᐊᕐᓂᒃ ᖃᐅᔨᓴᕐᓂᓂᑦ ᐃᓄᓐᓂᒃ, ᐃᓄᓐᓂᖕᒎᖅ ᖃᐅᔨᓴᖅᑎᖅᑲᖅᑐᓂ UL ᖃᐅᔨᓴᕐᓂᖅ ᐃᓄᓐᓄᑦ ᐊᐅᓚᑕᐅᓯᔪᓂ.

ᖃᐅᔨᓴᖅᑎᐅᖅᑲᑕᐅᒻᒥᔪᓂ ᑲᓇᑕᒥ ᓄᓇᓕᒻᒥ ᐱᒥᐅᓴᕝᕕᒃ ᐊᕙᑎᖓᓃᓕᖓᔪᓂᒃ ᑐᕌᖅᑐᒥᒃ ᐃᓗᓯᕐᓯᓯᐊᕐᓂᒧᑦ, ᐃᓚᐅᒻᒥᔪᓂ ᑐᑦᑕᕕᒻᒥᒃ ᖃᐅᔨᓴᕝᕕᒥ ᐃᓗᓯᕐᓯᓯᐊᕐᓂᒥᑦ ᐃᓄᓕᒫᓄᑦ ᐊᕙᑎᑦᑎᓂᓪᓗ ᑯᐯᒃ ᐃᓕᓐᓂᐊᕕᖕᒋᕝᕕᑎᖓᓂ ᒫᓐᑐᕆᐊᓪᒥ.

ᓵᓚᖃᖅᓯᒪᔪᖅ ᐱᓪᓚᕆᐅᑎᒥᔭᐅᓂᕐᒥᒃ ᐱᓇᓱᖅᑎᒌᑦᓯᐊᓂᕐᒥᒃ ᐊᕙᑎᑦᑎᓂᑦᑐᓂᒃ ᖃᓂᒪᓂᓚᓇᓂᕐᒥᒃ ᓚᕝᕖᑦ ᐃᓕᓐᓂᐊᕖᕐᔪᐊᖓᓂ. ᐋᔾᔨᑦᑕᐅᓂᖃᖅᓯᒪᑦᓯᓂ ᓱᑯᐃᔭᓂᕐᒥᒃ ᐊᒻᒪᓗ ᐃᓯᒪᓕᓇᓂᕐᒥᒃ ᐊᕙᑎᑦᑎᓃᓕᖓᔪᒥᒃ ᓱᑯᐃᔭᓂᕐᒥᒃ, ᐅᔾᔨᕐᑖᑎᑕᐅᓂᕐᒥᑦᓯᓂ ᐊᑕᓂᐊᓘᑉ ᑭᒡᒐᑐᕐᑎᖓᓄᑦ ᑲᓇᑕᒥ ᐊᒻᒪᓗ ᐱᓇᓱᒍᓇᑐᑦᑐᐊᖑᒍᓇᓂᖓ ᖃᓄᐃᙱᓯᐊᕐᓂᒧᓕᖓᔪᓂᒃ.

Appendix B


ᓇᓯᕝᕕᒃ
NASIVVIK
Chaire de recherche en approches écosystémiques de la santé nordique
UNIVERSITÉ LAVAL
CHU de Québec Université Laval
Centre de recherche
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Appendix C


ᓇᓯᕝᕕᒃ
NASIVVIK
Research Chair in Ecosystem Approaches to Northern Health
Understanding the links between northern ecosystems and health to mobilise knowledge into action
UNIVERSITÉ LAVAL
CHU de Québec Université Laval
Centre de recherche
© Pierre Dunnigan

Appendix D

ᖃᓄᐃᓕᕐᐱᑖ 2017 – ᓄᓇᕕᒻᒥ ᐃᓅᓯᕐᒨᓕᖅᒐᔪᓂᒃ ᐊᐱᕐᓱᓂᖅ ᐱᓇᓱᐊᕿᑦᓴᖅ

ᖃᖓ: ᐊᐅᒡᒍᓯ 8, 2017-ᒥ ᓯᑦᑎᒻᐱᕆ 26, 2017-ᒧᑦ **ᓇᓂ:** ᓄᓇᕕᐅᑉ ᓄᓇᓕᖏᓐᓂ 14-ᓂ **ᖃᓄᖅ:** ᐊᒪᓐᑦᓴᓐ ᐅᒥᐊᕐᔪᐊᖅᑯᓂ

ᐱᓂᐊᕐᓂᖅᒥᑦ
ᖃᐅᔨᓴᕐᓃᑦ ᐃᓄᐃᑦ ᐃᓅᓯᖅᒥᑦ ᖃᓄᐃᓕᖅᓂᖅᒥᓐᓂᒃ ᐱᔭᕆᐊᑐᔪᒻᒪᕆᐅᔾᔪᖅ ᓄᓇᕕᒻᒥ ᐃᓅᓯᓕᕆᓂᐅᑉ ᐊᐅᓚᑦᓯᔨᖅᒥᓇᑦ. ᑯᐯᒃ ᓄᓇᓕᕐᑯᑎᖅᒥᑦᑕ ᐊᓯᖅᒥᑎᑐᖕᒥᑐᖅ, ᐋᓂᐊᓂᓕᕆᓂᒃᑯᑦ-ᐊᐅᓚᑦᓯᕕᖅᓚᑕ ᐊᓪᓚᓯᒪᔪᕐᑯᑎᖅᒥᑦ ᐊᑐᕐᑕᐅᕐᑲᔭᖕᒥᑐᑦ ᓄᐃᑦᓯᒍᑎᐅᔪᑎᑦ ᖃᓄᐃᓕᔪᕐᑲᕐᓂᒪᖅᓖᑦ ᖃᓄᐃᑦᑐᒪᖅᓖᑕᔪ ᖃᓂᒻᒪᓯᐅᔪᐃᑦ ᓄᓇᕐᑯᑎᖅᓚᓂ. ᑯᐯᒃᑯᑦ ᑲᓇᑕᒃᑯᔪ ᐊᐱᕐᓲᔭᕈᑎᕕᓂᖅᒥᑦ ᖃᓂᒻᒪᓯᐅᔪᓂ, ᐃᓅᓯᓇᔭᐅᔪᓂᑦ ᐊᓯᖅᒥᓐᓂᔪ ᐃᓅᓯᕐᒨᓕᖅᓚᔪᑦ ᑲᒪᒍᑎᕕᓃᑦ 49 ᐃᑰᑕᖅᓚᑕ ᑕᕐᕿᖅᓚᓅᓚᐅᕐᓯᖅᖅᒥᑐᑦ. ᐊᒥᓱᓂᑦ ᐱᑦᔪᑎᕐᑲᕐᓱᓂ: ᐅᕐᑲᐅᓯᕐᑎᒍᑦ ᐃᓗᕐᕿᓯᑎᒍᓪᓗ ᐊᕝᕕᐊᓗᑕᕐᑲᕐᑯᑦ, ᐱᓂᐊᓚᑦᓴᖅᒥᑦ ᐱᓪᓗᑯᒥᐊᓕᑎᒍᓪᓗ ᐃᐸᒥᔭᐅᒥᐊᕐᑲᕐᒥᔪᑦ, ᖃᓄᐃᓘᕿᓯᐅᔪᓂᑦ ᐋᕐᕿᒥᐊᓇᓃᑦ ᐃᓂᕐᕋᐅᑏᓪᓗ ᐊᑭᖅᒥᑦ. ᒦᓇᐅᑎᓪᓗᒍᓕ, ᐊᐱᕐᓲᔭᕐᓂᕐᑲᓯᒪᓕᕐᑯᑦ ᒪᕐᕿᕕᑦᓯᑎᑦ ᓄᓇᕕᐅᑉ ᐱᒍᑦᔨᔨᖅᒥᑦ: 1992-ᒥ 2004-ᒥᓪᓗ. ᑐᖁᓚᐅᓚᓯᑦᑐᖅ ᖃᓄᐃᓕᕐᐱᑖ 2017 ᐊᐱᕐᓯᑲᑦᑕᓂᖅ ᐱᓇᓱᐊᕐᑕᐅᔪᑦᓴᖅ ᓄᐃᑦᓯᒪᓯᓪᓗᑎᑦ ᒦᓇᐅᓕᕐᑎᓗᒍ ᐃᓅᓯᖅᒥᑦ ᖃᓄᐃᓕᖅᓕᕐᒪᖅᓖᑕ ᐃᓄᐃᑦ ᓄᓇᕕᒥᐅᑦ.

ᕕᕿᐊᓇ 2014-ᒥ, ᓄᓇᕕᒻᒥ ᐃᓅᓯᓕᕆᓂᕐᒧᑦ ᐃᓄᓕᕆᓂᕐᒧᓪᓗ ᐱᒍᑦᔨᕕᖅᓚ, ᑭᒡᓚᑐᕐᑎᖅᒥᑦ ᓄᓇᓕᓕᒫᓂᑦ 14-ᓂᑦ ᐊᑐᓂᒃ ᐃᓚᐅᔪᕐᑕᕐᑲᕐᒥᓯᑎᓗ ᒪᕐᕿᓂ ᐋᓂᐊᕖᓐᓂ, ᐊᖅᒥᕐᑐᐃᓇᐅᑦᓯᑎᑦ ᑲᔪᓯᕐᑎᓯᓐᓂᕐᑯᑦ ᑐᑭᑖᕿᑎᒥᒃ ᓄᑖᒥᒃ ᐊᐱᕐᓲᔭᕐᓂᒥᒃ ᓄᐃᑦᓯᒪᔭᕐᑐᒥᒃ ᐱᖅᓚᓱᓂᑦ ᐃᓄᓕᓕᒻᒥᒃ: ᐃᓄᒻᒪᕆᓐᓂ ᐃᓅᓰᑦ, ᐃᓅᓯᑦᑐᓂᑦ ᐃᓅᓰᑦ, ᓄᓇᓕᐅᓪᓗ ᐃᓅᓯᖅᒥᑦ. ᐊᐱᕐᓲᔭᕐᓂᖅ ᐊᑑᑎᓚᔭᕐᑐᖅ ᓄᓇᕕᐅᑉ ᓄᓇᓕᓕᒫᖅᒥᓐᓂᑦ, ᐃᑲᔪᕐᓯᓗᓂ ᖃᓄᐃᓕᖅᓚᓚᓯᒍᑎᐅᔪᓂᑦ ᓄᓇᓕᓕᒫᓄᑦ ᐸᕐᓇᓯᒪᐅᑎᒧᑦ.

ᐱᑦᔪᑎᖅᒥᑦ ᐊᐱᕐᓲᔭᕐᓂᒥᑦ

- ᓄᑕᐅᓯᓕᕐᓯᒪᑦᓯᐊᑐᓂᒃ ᖃᐅᔨᓴᕿᑎᕕᓂᕐᓂᒃ ᐱᑖᓖᕐᒪᑦ ᓄᓇᕕᒥᐅᑦ ᐃᓅᓯᖅᒥᑦᑕ ᖃᓄᐃᓕᖅᓂᖅᒥᓐᓂᑦ.
- ᐊᓪᓚᕐᑯᑎᒨᕐᑐᒥᑦ ᓄᐃᕚᓪᓕᐊᔪᑦ ᓄᑖᑦ ᐃᓅᓯᓇᔭᐅᓕᕐᑐᑦ ᐃᓅᕐᑲᑎᕆᑦᑐᑎᒍᓪᓗ ᐱᖁᓗᑌᑦ ᑲᒪᒥᔭᐅᓗᑎᓪᓗ ᐅᕐᑲᕐᑕᐅᓯᒪᔪᐃᑦ ᖃᓄᐃᓕᖅᓂᐅᔪᐃᑦ: ᐃᓅᓯᑦᑐᐃᑦ ᐃᓅᓯᖅᒥᑦ, ᓄᓇᓕᐅᑉ ᐃᓅᓯᖅᒥᑦ, ᐊᑕᑯᑖᑦᑐᒥ ᖃᓂᒪᓰᑦ, ᓂᕿᑦᓯᐊᕐᑲᖅᖅᒥᓃᑦ, ᐃᓯᒪᒧᑦ ᐃᓅᓯᕐᓯᓯᐊᖅᖅᒥᓃᑦ, ᐊᕐᓯᕿᓴᕐᓃᑦ, ᐃᒻᒥᓂᐊᕐᓃᑦ, ᐊᔪᓇᒪᓇᕐᑐᐃᑦ, ᐱᑐᑲᓐᓃᑦ, ᐊᓯᖅᒥᓪᓗ.
- ᖃᐅᔨᓕᐅᒥᑐᑎᑦ ᓱᕐᕚᓂᖅᒥᓐᓂᑦ ᐱᕙᓪᓕᐊᓂᐅᔪᐃᑦ ᐸᕐᓇᓯᒪᐅᑏᑦ ᑕᕐᕿᒥ ᐃᓅᓯᕐᓂᒃ ᖃᓄᐃᖅᖅᒥᓯᐊᕐᓂᒥᓪᓗ ᓄᓇᓕᓐᓂ. ᐱᒪᓇᐅᔪᓇᔭᐅᔾᔪᖅ ᐊᓪᓚᕐᑯᑎᒨᕐᑎᓯᓂᖅ ᐃᓅᓯᓇᔭᐅᓕᕐᑐᒥᒃ ᒦᓇᐅᓕᕐᑐᖅ ᐃᓄᕐᑯᑎᖅᒥᓐᓄᑦ ᓯᕗᓂᑦᓴᒥ ᖃᓄᐃᓕᖅᓂᖅᒥᑦ ᑕᑯᓐᓇᑕᐅᔪᑦᓴᒦᖅᒍᓚᔭᕐᑐᑎᒃ.
- ᖃᐅᔨᒪᒍᑎᑦᓴᑖᓖᕐᒪᑕ ᐃᑲᔪᕐᓯᒍᑎᑦᓴᓂᒃ ᐋᓂᐊᓂᓕᕆᓂᒃᑯᑦ ᐱᓇᓱᐊᕿᑦᓴᓂᒃ ᑲᔪᓯᑎᑦᓯᓚᓯᑦᑐᓂᑦ ᓄᑖᓂᒃ ᖃᓄᐃᓘᕿᑎᑦᓴᓂᑦ ᐱᒍᑦᔨᓂᕐᓂᓗ ᐱᓇᓱᖅᑎᕐᑦᑐᑎᑦ ᓄᓇᓕᐅᔪᐃᓪᓗ, ᐱᓇᓱᐊᕐᑐᑎᑦ ᐱᕚᓪᓕᐊᕐᑯᑐᒥᑦ ᓲᖅᒍᓯᑎᒥᐊᕐᑐᒥᓗ ᐱᒍᓇᓂᖅᒥᑦ.

ᓂᕆᐅᒥᔭᐅᔪᖅ ᑲᔪᓯᑯᑖᓕᖅᓚᒥᐊᖅᒥᑦ ᓄᑖᖅ ᐊᐱᕐᓲᔭᕐᓂᖅ ᐊᐱᕐᓲᔭᕐᓂᐅᓯᒪᔪᐃᓪᓗ ᐊᓯᑦᓯᕙᓪᓕᐊᓂᕆᓯᒪᔭᖅᒥᑦ ᖃᓄᐃᓕᖅᓂᐅᔪᐃᑦ ᓱᕐᑯᐃᑐᒥᒃ ᖃᐅᔨᒥᐊᕐᑕᐅᓂᐊᕐᓚᑕ. ᐅᓇᓗᑦᑕᐅᖅ, ᓄᑖᖅ ᐊᐱᕐᓲᔭᕐᓂᐅᓚᖅᓚᔪᖅ ᐊᐱᕐᓯᕿᓯᑐᕐᑲᐅᓰᑦ ᐅᖅᓚᑖᓄᕿᓯᑦᑐᖅ, ᑲᓯᕐᑎᓯᒥᑦ ᒦᓇᐅᓕᕐᑐᖅ ᖃᓄᐃᓕᖅᓂᐅᓕᕐᑐᐃᑦ ᖃᐅᔨᕙᓪᓕᐊᒍᑎᓕᒥᓗᒥᑦ ᓄᓇᖃᖅᖃᓯᒪᔪᑦ ᓄᓇᓕᖅᒥᓐᓂ, ᐊᓪᓚᓯᒪᔫᑦᓯᐊᕐᑯᑦᓯᒥᑦ ᖃᓄᐃᓕᖅᓂᓇᔭᐅᔪᑦ ᐃᓅᓯᑦᑐᓂᑦ ᓄᓇᓕᐅᔪᓂᓪᓗ.

Appendix E

COMMENT ÉVITER LE PLOMB DANS LES MUNITIONS ?

Chasser et manger de la viande de chasse est super pour la santé, surtout lorsqu'on réussit à éviter le plomb !

Pourquoi il est important d'essayer d'éviter les munitions qui contiennent du plomb ?

- Le plomb est toxique : il nuit au développement normal du cerveau du fœtus et des enfants.
- Les cartouches avec des billes de plomb (aussi appelées grenaille de plomb ou chevrotine de plomb) ou les balles avec une tête en plomb libèrent une quantité importante de plomb dans la terre, dans les rivières et dans les lacs.
- Une fois dans l'environnement, le plomb contamine les oiseaux et les poissons et peut avoir des effets toxiques sur la santé des oiseaux et des poissons.
- Les cartouches avec des billes de plomb ont été interdites au Canada pour protéger la santé des oiseaux qui vivent près des rivières et des lacs.

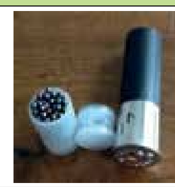
Comment les munitions peuvent exposer les femmes enceintes, les enfants et les adultes au plomb?

- La viande des oiseaux ou de petit gibier chassés avec des cartouches avec des billes de plomb peut-être contaminée au plomb : on trouve dans la viande des billes de plomb ou même des petits fragments de plomb invisibles à l'œil nu.
- La viande de gros gibier chassée avec des balles de plomb peut aussi être contaminée au plomb : lorsque la balle pénètre et explose dans la chair de l'animal, elle libère des petits fragments de plomb, surtout dans le sillage de la trajectoire de la balle et autour de l'impact de la balle.
- Lorsqu'on nettoie les armes avec lesquelles des munitions de plomb ont été utilisées, les poussières qui sortent de l'arme contiennent du plomb.
- Lorsqu'on fabrique des munitions au plomb (cartouches avec billes de plomb) avec les mains ou qu'on touche à des munitions ou à des poussières contenant du plomb (par exemple chez les enfants qui marchent à quatre pattes et ceux qui jouent avec des cartouches de plomb intactes ou utilisées).
- Les chasseurs qui chassent avec des munitions de plomb respirent de la fumée contenant du plomb lorsqu'ils tirent.

Bonne nouvelle ! Il existe des munitions sans plomb !

À ÉVITER!
Munitions avec des billes en plomb
Interdite pour les oiseaux migrateurs

SANS PLOMB!
Munitions avec des billes en acier
Disponibles dans la plupart des calibres
Moins chères que celles en plomb

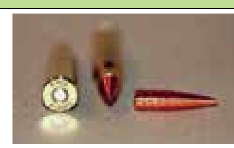


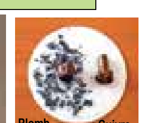
SANS PLOMB!
Munitions avec des billes en bismuth ou en tungstène
Disponibles dans la plupart des calibres, mais un peu plus chères que celles en acier

Il existe aussi des balles sans plomb !!

AVEC DU PLOMB!
Balles avec une tête en plomb
Toujours sur le marché

AVEC DU PLOMB!
Balles avec une tête recouverte de cuivre mais avec l'intérieur en plomb



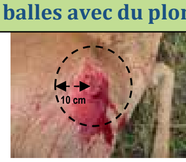


Meilleure option !

SANS PLOMB!
Balles 100% en cuivre (recouvrement et intérieur en cuivre)
Mais un peu plus chères que les autres

Comment éviter le plomb si vous chassez avec des balles avec du plomb?

Enlever <u>10cm de viande</u> autour de l'impact de la balle permet d'éliminer une grande partie des fragments de plomb dans la viande



Les lance-pierres, les arcs à flèches et les arbalètes sont aussi super pour éviter le plomb!

Pour plus d'informations, contacter le projet JES !-YEH !:
Joao-Carlos.Guedes-de-Oliveira@crchudequebec.ulaval.ca

Appendix F

ᓯᓚᓂᐊᒼ ᓄᓇᕕᒻᒥᐅᓃᑦᑐᖅ ᐃᓄᐃᓪᓗ ᓂᕿᑐᐃᓐᓇᕆᓐᓂ

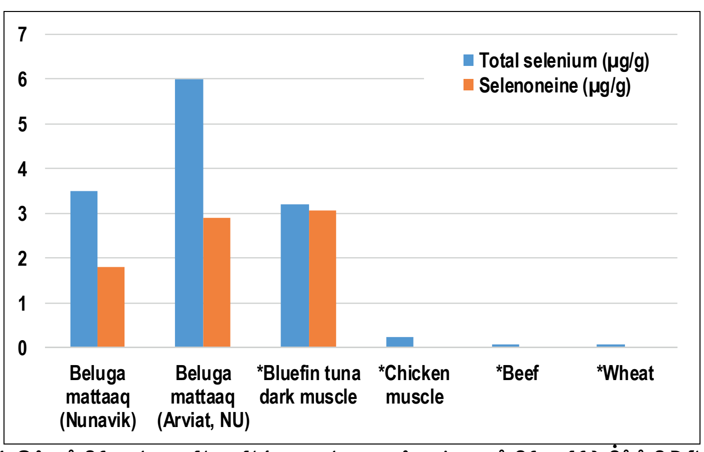
- ᓯᓚᓂᐊᒻᒥᒃ ᐱᑕᖅᑳᓪᓚᕆᐊᓕᒃ; ᑖᑦᓯᒪ ᐃᓚᖓᓂᒃ ᐱᑕᖃᕆᐊᖃᕐᖁᒍᑦ ᑎᒥᕗᑦᑕ ᐊᒥᓯᓛᐅᑦᓯᑎᑦ ᐃᓂᕋᒍᑎᑦᓴᕆᓐᓂᑦ ᐆᑦᑑᑎᒥᓗᒍ ᓴᕘᓗᑕᒥᓗᒍ ᓱᒃᑯᓇᖅᑑᒍᓐᓇᑐᓂᑦ (ᓱᒃᑯᓇᖅᑐᐃᑦ ᐱᖁᑏᑦ) ᑎᒥᕗᓐᓂ ᐊᒻᒪᓗ ᖁᖓᓯᕐᒥᑐᑦ ᓴᕘᓗᑌᑦ.
- ᓯᓚᓂᐊᒼ ᓇᙵᑕᐅᒍᓐᓇᑐᖅ ᐊᒥᓯᑕᖃᕐᓯᓂ ᓂᕿᑐᐃᓐᓇᓂᑦ ᓂᕆᔭᐅᓰᓂᑦ ᐃᓄᓐᓄᑦ, ᐱᓗᐊᖅᑐᒥ ᐃᒪᕐᒥᐅᑕᓂ ᐆᑦᑑᑎᒥᓗᒍ ᕿᓚᓗᒐᐅᑉ ᒪᑦᑕᖓᓂ, ᐁᕕᐅᑉ ᓂᕿᖓᓂ, ᐃᒪᕐᒥᐅᑌᑦ ᐃᖅᑲᕕᖕᒥᓐᓂᑦ ᐃᖃᓗᓪᓗ ᓯᕙᖕᒥᓐᓂ.
- ᓯᓚᓂᐊᒼ ᐳᖅᑐᓂᖕᒥᑦ ᐊᐅᒻᖕᒥᓐᓂ ᓄᓇᕕᒻᒥᐅᑦ ᓂᕿᑐᐃᓐᓇᑐᓇᑐᓰᓂᑦ ᐆᑦᑑᑎᒥᓗᒍ ᒪᑦᑕᒥᒃ ᐳᖅᑐᓂᖅᐸᐅᕗᑦ ᓯᓚᖅᖁᐊᓚᒦᒥ. ᑌᒣᓚᖓᒥᕗᖅ ᓄᓇᓄᒻᒥᐅᑦ ᐊᑯᑭᑦᑐᒥᐅᓪᓗ.
- ᒦᓐᓇᖅᑲᒻᒥᒃ, ᓄᑖᒥᒃ ᐅᐊᕿᑦᓯᓯᒪᔪᒥᒃ ᑌᔭᐅᔪᒥᒃ ᓯᓚᓄᓈ ᖃᐅᔨᔭᐅᓯᒪᓚᓐᕗᖅ. ᓯᓂᓄᓈ ᐃᓗᓚᑕᓚᒃ ᓴᐳᒻᒥᒍᓐᓇᑐᒥᒃ ᑎᒥᒥᒃ ᓱᒃᑯᓇᖅᑐᓂᑦ (ᐃᑲᔪᖅᓯᒍᓐᓇᑐᖅ ᑎᒥᒻᒥᒃ).
- ᓯᓚᓄᓇᐃᓐ ᖃᐅᔨᔭᕕᓂᖅ ᐊᒥᓯᑳᓚᐅᓯᑎᑦ ᓯᓚᓂᐊᒻᒥ ᐃᖅᑲᓗᒻᒥ ᑌᔭᐅᔪᒥ ᐳᓗᕕᓐ ᐊᒻᒪᓗ ᐊᓯᖕᒥᓐᓂᑦ ᐃᖅᑲᓗᓐᓂᑦ. ᐳᖅᑐᔪᕚᓗᓐᓂᑦ ᓯᓚᓄᓈ ᓇᙵᑕᕕᓃᑦ ᔫᐸᓂᓰᑦ ᐊᐅᖕᒥᓐᓂ ᐃᖅᑲᓗᑦᑑᒪᓰᓂᑦ.
- ᖃᐅᔨᔭᐅᕙᓪᓚᐊᑐᐃᓐᓇᑐᖅ ᓯᓚᓂᐊᒼ ᐃᑲᔪᖅᓯᑐᐃᓐᓇᕆᐊᖃᖅᓂᖓᓂᒃ ᑎᒥᕗᓐᓂᑦ ᕚᓐᓂᓗᓂ ᒧᒃᑯᕆᐅᑉ ᓱᒃᑯᓇᖅᓂᖕᒥᓐᓂᑦ. ᓯᓚᓄᓈ ᒧᒃᑯᕆᓗ ᑕᒪᒥᑦ ᓄᐊᓰᑦ ᐊᐅᐸᓗᑦᑖᐱᒻᒥ ᐊᐅᒻᒥ; ᓯᓚᓄᓈ ᐳᖅᑐᓯᐅᒥᑎᑦᓯᒍᓐᓇᑐᖅ ᓱᒃᑯᓇᖅᑐᐃᔪᓂᖅᒥᒃ ᒧᒃᑯᕆᒥᒃ ᐳᒃᑭᓕᐅᒥᑎᑦᓯᓗᓂᓗ ᖃᕆᑕᒨᔭᖅᓂᖕᒥᓐᓂᑦ.

ᒦᓐᓇᖅᑲᒻᒥᒃ, ᐱᓇᓱᖃᑎᕇᑦᑑᔪᒍᑦ ᐱᓇᓱᐊᖅᓯᒪᔪᒍᑦ ᖃᐅᔨᒪᓱᑦᓱᑕ ᓯᓚᓂᐊᒼ ᖃᓄᐃᑦᑑᓂᖕᒥᓐᓂᑦ ᓄᓇᕕᒻᒥ. ᖃᐅᔨᖅᖃᒥᕗᑦ ᓄᐃᑕᑎᑦᓯᕗᑦ ᐃᒦᒃ: → **ᐳᖅᑐᔪᐸᐅᔫᓗᒥᐅᖅᓱᓂ ᓯᓚᓄᓈ ᐳᖅᑐᓂᖕᒥᑦ ᓇᙶᑕᐅᓯᒪᕗᑦ ᐃᓄᐃᑦ ᐊᐅᖕᒥᓂ ᐊᐅᐸᓗᑦᑖᐱᓐᓂ;** ᓄᓇᕕᒻᒥᐅᓂ ᓂᕆᓰᓂᑦ ᕿᓚᓗᒐᐅᑉ ᒪᑦᑕᖓᓂᒃ ᐳᖅᑐᔪᐹᓗᓐᓂᑦ ᓯᓚᓂᐊᓖᑦ ᐊᐅᒥᓂ, ᓯᓚᓂᐊᒼ ᓇᙵᑕᐅᕙᓪᓗᓰᖅ ᓯᓚᓄᓈᒥ. → **ᐳᖅᑐᔪᐸᐅᔫᓗᒥᐅᖅᓱᓂ ᓯᓚᓄᓈ ᐳᖅᑐᓂᖕᒥᑦ ᓇᙵᑕᐅᓰᑦ ᕿᓚᓗᒐᐅᑉ ᒪᑦᑕᖓᓂ ᓄᓇᕕᒻᒥ ᐊᒻᒪᓗ ᐊᖅᕕᐊᒥ** (ᓄᓇᕗᑦ). ᖃᐅᔨᓴᖅᑕᐅᕙᓪᓚᐊᒥᔪᑦ ᐊᓯᖕᒥᑦ ᓂᕿᑐᐃᓐᓄᑦ.

ᐊᑦᔨᖑᐊᖅ 1: ᐊᒥᓱᑳᓗᑦ ᓯᓚᓄᓈ ᐊᒻᒪᓗ ᑲᑎᓚᒦᖅᓂᖕᒥᑦ ᓯᓚᓂᐊᒼ ᐊᐅᒻᒥ ᐊᐅᐸᓗᑦᑖᐱᓐᓂ ᐃᓄᐃᑦ ᐃᓄᒻᒪᓇᖕᒥᓐᓂᑦ

ᓯᓚᓂᐊᒼ ᐊᑦᔫᖕᖕᒥᑐᑦ	ᐃᓄᐃᑦ ᐃᓄᒻᒪᓈᑦ
ᓯᓚᓄᓈ	123.1 (0-2707.7)
ᑲᑎᓐᓂᖕᒥᑦ ᓯᓚᓂᐊᒼ	383.40 (174.7-3134.7)

*µg Selenium/L; median (ranges)



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Mobilizing Knowledge Through a Network of Inuit Educational Leaders and Researchers: Bilingual Education in Inuit Nunangat

Project Leader

Alexander McAuley (University of Prince Edward Island)

Network Investigator

Fiona Walton (University of Prince Edward Island)

Collaborators

Louise Flaherty (Nunavut Arctic College - Nunatta Campus)
Mark Sandiford (Beachwalker Films)
Becky Tootoo (Government of Nunavut)
Shelley Tulloch (University of Prince Edward Island)

HQP

Naullaq Arnaquq, Doctoral Student (Government of Nunavut)
Cathy Lee, Doctoral Student (University of Toronto)
Yemi Oolajide, Masters Student (University of Prince Edward Island)
Jupeeka Hainnu, Research Associate (Community of Clyde River)
Nunia Qanatsiaq, Research Associate (Government of Nunavut)

ABSTRACT

"Mobilizing Knowledge Through a Network of Inuit Educational Leaders and Researchers: Bilingual Education in Inuit Nunangat" is an innovative research initiative using digital technologies to harness the expertise of Inuit and non-Inuit parents, educators, researchers and collaborators to develop and share effective, research-supported, bilingual education strategies across Inuit Nunangat. Bilingual education that builds on research knowledge as well as knowledge held in Inuit communities is critical to the future economic, cultural and linguistic success of Inuit in Canada. It contributes to student learning at the school and post-secondary levels in the educational system and through this contributes to the strength and vitality of Inuit society. The development of a bilingual, responsive Inuit workforce, well-prepared for current and future economic opportunities is vitally important at this time. Using a grassroots, community-based approach, this initiative is poised to make a significant contribution to the well-being and sustainable future of Inuit in the Canadian Arctic.

KEY MESSAGES

- Cultural identity as manifested in mother-tongue (Inuktut) acquisition is critical to both academic success and second language acquisition.
- The connections between bilingual education and other issues in Inuit education, including attendance, truancy, retention, parental disengagement, need to be stressed.
- Bilingual, plain language summaries of key points can be effective tools.
- Non-Inuit "allies" can provide support.
- Factors contributing to successful Inuktut acquisition for children include strong language support in the home, giving Inuktut prominence, emphasizing the connections between orality and literacy, and language-rich environments.
- Public and professional discourse about bilingual discourse (e.g. among teachers, parents) reflects ongoing misunderstandings about the processes and outcomes of bilingual education.
- Discrepancies persist between favourable policies and actual implementation; parents, teachers, and principals wield a great deal of influence in whether and how bilingual education policies are implemented.
- Current processes and outcomes of bilingual education in Nunavut need to be understood in light of power relations, ideologies about language, bilingual learners, and education, as well as in light of the shifting bilingual context and history of schooling in the North.

OBJECTIVES

We continued to pursue the three objectives set forth in our original proposal, approved in November, 2014, namely to:

1. Facilitate informed dialogue among Inuit educational leaders, parents, community groups (such as Nunavut District Education Authority members), teachers, administrators, curriculum developers, policy makers and emerging scholars regarding current challenges, successes, and promising avenues for improving and enhancing bilingual education within Inuit schools and communities;
2. Analyse, synthesize and compare the recent and relevant scholarly literature related to legislation, policies, and promising practices in bilingual education in Inuit communities in Canada;
3. Mobilize and disseminate knowledge based on evidence-based practices in bilingual education with relevant application to Inuit Nunangat, including creation of short informational videos that act as learning modules targeted at the public, parents, teachers and all decision makers.

INTRODUCTION

As stated in the National Strategy for Inuit Education, bilingual (Inuktut and English/French) education is seen as critical to the improvement of both educational engagement and outcomes in Inuit Nunangat (National Committee on Inuit Education, 2011). Land claims and self-government agreements across Inuit Nunangat have opened possibilities for alternatives to the assimilationist policies and institutions that have undermined Inuit language, culture, and well-being. These agreements have further affirmed Inuit's right to manage their own educational systems.

Canadian Inuit's right to education in Inuktut was first recognized in Nunavik in 1964, and entrenched in the James Bay Northern Quebec Agreement in 1975. Since 1971, Northwest Territories policies have allowed for Inuktut mother tongue education. The Inuvialuit Final Agreement (1984) created the Inuvialuit Social Development Program to address ongoing Inuit-specific concerns in education and maintenance of traditional practices (among others). In Nunavut, the right to Inuktut language education is affirmed in the *Inuit Language Protection Act* (2008). Nunavut's *Education Act* (2008) mandates a strong model of bilingual education. The Labrador Inuit Land Claims Agreement (2005) recognizes Inuit's right to use Inuktut and established the Nunatsiavut self-government with authority over Inuit education.

School administrations in each region have made efforts to actualize Inuit's right to learn Inuktut alongside a national language. In Nunavut and Nunavik, where most Inuit still learn Inuktut as the mother tongue, efforts have included strong mother tongue education from Kindergarten to Grade 3, with efforts to expand Inuktut learning through to Grade 12. Students in Nunavik must pass Grade 12 final Inuktut exams to complete their provincially-recognized high school diploma. In Nunatsiavut, the Inuvialuit Settlement Region, and some western Nunavut communities, where Inuktut is less frequently the mother tongue, efforts have been made to introduce Inuktut immersion programs. School-based efforts are reinforced by community efforts supporting lifelong learning, including early childhood programs, land or culture-based programs, and others.

Despite these acknowledged rights and efforts, parents, youth, teachers and others across Inuit Nunangat communities are increasingly concerned that young people have inadequate opportunities to achieve high levels of bilingualism. Knowledge and use of Inuktut are decreasing. As they see their children struggling at school, a tendency has been to blame bilingual education, rather than acknowledge it as part of the solution. These concerns are explicit in Nunavut's controversial Final Report of the Special Committee to Review the *Education Act* (2015), which openly suggests weakening Nunavut's commitment to Inuktut education. However, they are also seen in parents' implicit choices, for example in not choosing Inuktut immersion for their child, even when available.

International research indeed supports bilingual education as a desirable and effective education model for students from any background. Research in the wider Canadian context has documented that English mother-tongue students in French immersion schools in Québec and Ontario can achieve bilingual fluency and literacy as well as equivalent or superior academic performance to their monolingual peers (Cummins, 1998). Maori, Hawaiian, Mohawk, and Navajo case studies take these findings further, showing how Indigenous students benefit from immersion education in their ancestral language as a vehicle for language reclamation and as a way of recreating culturally affirming schools that support student perseverance and success (May et al. 2006; Reyhner, 1990; Todal, 2003).

Mother tongue and culturally-responsive education has long been established as a promising model, particularly for students from minoritized communities who might experience multiple barriers to feeling welcome and thus learning and persevering in schools (UNESCO, 1953; Thomas and Collier, 2002). Rigorous research spearheaded by the Kativik

School Board over twenty years and in fourteen Nunavik communities consistently demonstrated that Inuit students who had Inuktut as their language of instruction from Kindergarten through to Grade 3 had, by the end of Grade 3, higher self-esteem, greater knowledge of Inuktut, and stronger or comparable knowledge of English than their peers educated in the English language stream (Taylor and Wright, 2003). These results are repeated in bilingual education programs across the world which prove that being educated in two languages ultimately leads to greater proficiency in both languages, because language competencies transfer between languages.

Furthermore, research with post-secondary students confirms that a grounding in one's identity, culture, and language supports persistence in college and university (Fuzessy, 2008).

The challenge, then, is achieving a synthesis of the expressed desire for robust bilingualism in Inuit Nunangat, identifying what research has demonstrated about bilingual education in the larger context, and suggesting the practices that may enable them to come together. The research conducted to date as part of the Akuttujuuk network suggests a need for activism and informed public discourse about the contribution of effective bilingual education to student success in order to challenge the perception of a sub-section of the population that believes (against research evidence) that English-language education will lead to greater student success.

Much of the basis for this activism and discourse currently exists at the community level, where innovative educators, including graduates of Northern teacher education programs and the Nunavut Master of Education (MEd), create and adapt materials and pedagogies to create rich bilingual learning environments for their students. Often, however, these educators work in relative isolation, separated by vast distances, small populations, and relatively high turnover among their teaching colleagues. The goal of Akuttujuuk, the Inuit Educators' Research Network, is to create an infrastructure and a range of resources that will allow educators and any others interested in the best possible education for the young people of Inuit Nunangat to support each other in the development, sharing, adaptation, and implementation of approaches to bilingual education that will contribute to addressing the issues raised in the National Strategy.

ACTIVITIES

From November 2014 to present, the Akuttujuuk research team has engaged in the following activities, aimed at invigorating community-level knowledge sharing about what is working and what is needed to enhance bilingual education in Inuit Nunangat.

Online Presence (Infrastructure)

- Maintained and extended the social media presence via the private Akuttujuuk Facebook group and the Twitter @Akuttujuuk handle.
- Established a bilingual web presence via a custom WordPress site at www.akuttujuuk.ca.
- Created a dedicated Akuttujuuk channel on isuma.tv to facilitate access to multimedia materials across Inuit Nunangat www.isuma.tv/video/akuttujuuk.
- Created a private, interactive learning and collaborative workspace for Network members (Knowledge Forum®).

Field Research - Arviat - March/April 2015

- "What works in bilingual education?" research fieldwork in Arviat, NU (March 30-April 2, 2015) to gather video data for the first set of video modules on community-based bilingual education. After obtaining REB approval and NRI licensing, researchers and a film-maker travelled to Arviat to work with Akuttujuuk Network member, MEd graduate, and Inuit community researcher, Nunia Anoee.

- Data analysis and knowledge translation production workshop in Winnipeg, MB (July, 2015) to begin preparation of bilingual discussion modules.
- Six bilingual (Inuktut/English) multimedia presentations on community-based factors contributing to effective bilingualism developed in collaboration with our partner, the Coalition of District Education Authorities of Nunavut, based on interviews and literature.

Meetings and Workshops (Collaboration)

- Network team meetings and information sessions held at the Qikiqtani Regional Teachers' Conference in Iqaluit, NU (February 18, 2015), the NS@30 (Nunavut Sivuniksavut) Conference in Gatineau, QC (April 25-27, 2015) and the ArcticNet ASM Vancouver (December 7-11, 2015). Meetings included academic team members, Network members, and contacts from Inuit governments and land claims organizations.
- Video interviews with community members and/or key knowledgeable individuals at NS@30.
- Online facilitators' planning meeting and workshop in Toronto, ON (July, 2015).
- Video interview with Dr. Jim Cummins, global expert on bilingual education in Toronto, ON (July, 2015).
- Meeting and video interview with Jason Annahatak, director of post-secondary studies at Kativik School Board (June, 2016). Part of the interview to be edited and posted to Akuttujuuk.ca website.
- Ongoing teleconferences between team members; phone calls between academic team members and members of the Akuttujuuk network; phone calls between team members and Inuit organizations.

Knowledge Syntheses

- Qualitative thematic analysis of new interviews (Arviat, key individuals) and existing corpora (Stepping Forward) using NVivo software for qualitative analysis. Led to two co-authored conference presentations and two journal articles (one accepted, one under review).
- Compilation of existing sources relevant to bilingual education in Inuit Nunangat. Led to the establishment of an online interactive database of sources on bilingual education using Zotero (Akuttujuuk Inuit Bilingual Education). Also led to the creation of a bibliography of sources relevant to bilingual education in Inuit Nunangat.
- Literature review of bilingual education, including legislation, policy documents, theoretical sources, local case studies, large scale quantitative studies and broad reviews of case studies. Led to one journal article (submitted); a framework for effective bilingual education posted to the website; a timeline of bilingual education posted to the website; a written literature review; and a series of blog posts to be released on Akuttujjuuk.ca over the summer and fall of 2016.
- Critical analysis of discourse about bilingual education, including literature and narratives. Led to two conference presentations.
- Establishment of an online interactive database of sources on bilingual education using Zotero (Akuttujuuk Inuit Bilingual Education) containing 65 sources, with full bibliographic references, abstracts or summaries, and full text or links to full text as available.

RESULTS

Our research asked the question, "Under which circumstances are Inuit educational leaders and researchers empowered to generate and communicate, as well as access, evaluate and apply various types of knowledge about quality bilingual education to improve educational outcomes in Inuit Nunangat?" The research question came from Inuit educators' expressed desire for ongoing professional development and a professional network for furthering their practice. The activities described above created frameworks for reciprocal generation, communication, and interpretation of knowledge about bilingual education.

The outcomes of each activity are reported in some detail below, organized according to the three categories of activities outlined above.

The analysis of these outcomes, presented in the discussion section following, suggests that University-community alliances can be empowering contexts for Indigenous-driven knowledge creation and mobilization. However, analysis of the project outcomes also suggests that in many ways Inuit educational leaders are disempowered from leading such knowledge generation, interpretation, and dissemination.

Online Presence (Infrastructure)

Creating the online infrastructure to support network activity and interaction was the first priority for 2015-16 as it provides the medium through which sharing, discussion and collaborative co-creation of resources can take place. The Akuttujuuk online presence has three components; 1) a private Facebook group for casual sharing and short discussions which fits into members' daily workflows; 2) a private discourse environment for more substantive collaboration provided via a Knowledge Forum® platform; 3) a public social media presence through the Akuttujuuk website and @Akuttujuuk Twitter feed.

Perhaps because it was the first online medium specifically dedicated to the network, the easiest to access, and closest to members' normal day-to-day routines, the Akuttujuuk Facebook group has been the most active. As of January 2016, it has 25 members from southern Canada, Nunavut, and Nunavik. The last twelve months have seen 77 individual postings, virtually all of them with multiple responses. Topics range from announcements of upcoming conferences and network members' activities, to sharing of online resources, to initial reactions to current events shaping bilingual education across Inuit Nunangat, such as the Final Report of the Special Committee to Review the Education Act in Nunavut and the Truth and Reconciliation Commission's Final Report. The Facebook group is used to share a network newsletter and provides a springboard to more extensive collaboration in the Knowledge Forum database.

We have found, in these ways, that the private Facebook group is a useful tool for facilitating networking and ongoing communication between the MEd graduates who often feel isolated as one of only two or three Inuit educational leaders in their community. We have also found it a useful tool for Network members keeping each other informed of significant events in bilingual education, and keeping each other informed of their own activities and presentations relative to bilingual education.

However, despite being a closed and private group, we have observed members being reluctant to go beyond surface-level exchanges on the Facebook page. Deeper critiques and responses to issues in bilingual education have been shared through private emails, and phone calls between researchers and Network members, but not on the private Facebook group. Comments from network members, as well as issues identified through the literature review (Arnaquq, 2008; Fyn, 2015; Kauki, 2015), suggest that some Inuit educational leaders feel disempowered from taking a public stance, either because they have already said the same thing so many times and not been heard, or because they have been censured for speaking up. These concerns effectively block their empowerment as locally-anchored Inuit scholars of education who would be most effective at creating, interpreting, and disseminating understandings about bilingual education in ways that have real impact in Inuit Nunangat. These concerns around silencing and being heard are avenues for further investigation in 2016-2017 (Figure 1).

The Akuttujuuk Knowledge Forum database was launched in May, 2015 as a secure online environment to be used to support more extended collaboration and discussion than the Facebook platform could sustain. Its 13 members have contributed to 12 ongoing discussions that include the Nunavut Education Act Review, the literature review on bilingual education, the Report of the Truth and Reconciliation Commission, and preparation for upcoming presentations.

Network members are familiar with this environment from their Masters of Education program. However, several reported that they had ongoing difficulties accessing and using Knowledge Forum® the way they wanted to. In part, this suggests that access Internet infrastructure is still insufficient (or too expensive) in Northern communities to support this high-level online networking (Figure 2).

Both of the previous two platforms are closed environments intended to support sharing and collaboration among network members. However, if the network is to achieve its goals, it must also have a public presence to extend the discussion and sharing about bilingual education to a wider audience. The bilingual Akuttujuuk website and blog was launched in April, 2015 to provide a central focus to support this goal; a Twitter handle, @Akuttujuuk, was also set up to supplement the website. To this point neither of these platforms have seen significant use by network members, although this is expected to change as the bilingual learning modules proposed for the project are posted and as key learnings from the literature review are crafted into short blog posts debunking common myths about bilingual education identified by Network members (Figure 3).

To support these initiatives, two network members, Cathy Lee (PhD Candidate at OISE/UT and an educator in Pangnirtung, NU) and Becky Tootoo (Teacher/MEd Graduate in Baker Lake, NU) have undertaken roles as network facilitators. A channel on Isuma TV has also been set up to share multimedia materials and a narrated version of one of the network's ArcticNet ASM presentations has been posted there as a test (http://www.isuma.tv/akuttujuuk/critical-analysis-of-discourse-about-bilingual-

Figure 1. The private Akuttujuuk Facebook group.

Figure 2. The Knowledge Forum Database.

education-in-nunavut). Since its posting in January 2016, it has received 411 views.

In all, the online tools have opened doors for ongoing networking and collaboration between Inuit educational leaders and the university-based team. However, they have not to date led to the breadth or depth of activity that would show they are truly empowering tools for Inuit-driven knowledge generation. Our experiences in the Nunavut Masters of Education program showed us that face-to-face meetings were essential for sustaining the online component of knowledge exchange (Wheatley et al. 2015), and we wonder if the lack of predictable in-person meetings between the broader network is a limiting factor in this network.

Field Research - Arviat - March/April 2015

The Executive Director and one member of the Nunavut DEA Coalition joined the researchers for this field research. Videotaped interviews related to bilingual education took place with parents, Elders, and DEA members. Meetings with educators in community schools and with the DEA in Arviat also took place. The DEA meeting was video-recorded. Transcripts of all video-tapes took place and were then analysed to inform the development of K2A learning modules.

While the online tools attempted to mobilize Inuit-driven knowledge creation and sharing across the Network, the Arviat field research mobilized knowledge among leaders in a particular community that is recognized for its success in graduating bilingual Inuit.

The Arviat field research was led by one of the network members, Nunia Qanatsiaq Anoee, supported by the university-based team. It brought together Inuit who are recognized as leaders due to degrees (MEd graduates), leadership positions (District Education Authority Board members), or family/community roles (Elders and parents). Even at the data collection level, this process mobilized “grassroots knowledge-making” (Canagarajah, 2005) as these knowledgeable and implicated community members shared with each other what they consider

Figure 3. Inuktut interface for the Akuttujuuk website.

to be working in bilingual education, as well as their concerns.

Data from the narratives were interpreted and contextualized to reflect how comments fit into literature about bilingual education, and how they fit into Nunavut context of bilingualism and bilingual education. Main findings from the Arviat research include:

- Arviat Inuit educational leaders conceptualized bilingual education as part of a lifelong process, beginning in the homes, supported by community, and continuing through adulthood (corroborated in other Inuit and Indigenous research contexts, e.g., Avataq, 2012; Government of Nunavut, Department of Culture and Heritage, 2012; Tulloch and Nunavut Literacy Council, 2009).
- Success in Arviat bilingual education is attributed to parents and community acting as empowered leaders, including through school engagement and family language policies (corroborated in Patrick et al. 2013; Simons, 2012; Smith, 1995; Tuafuti and McCaffery, 2005).
- Success in Arviat bilingual education is also attributed to rich contexts of Inuktut-only language use in the community, including community radio, land activities, and church services where children learn to read and write through singing and hymns.
- Educators and parents had different opinions about the impacts and desirability of language-of-instruction options. The ambivalence about different timelines and methods for introducing English is common in Indigenous bilingual education contexts. The research literature is also inconclusive (e.g., Cummins, 2000; Hornberger, 2009). These observations open the door to considering whether the focus on models and instructional minutes in each language could be distractions (Smith, 1999) from the real issues hindering effective education. This idea will be explored in 2016/2017.
- Attendance was a major issue participants wanted to discuss. These results also remind us that effective bilingual education is first and foremost effective education, built on pillars that are relevant to any model of education (e.g. appropriate resourcing, curriculum, leadership, teachers, support, infrastructure, information sharing, etc.).

Results were contextualized within network dialogue about the Truth and Reconciliation Commission's findings on the disruption of parental and community leadership in education, and the National Committee on Inuit Education's focus on family engagement. They were also contextualized in the history and current practices of bilingual education in the four Inuit regions. Findings will be presented at the international Etudes Inuit Studies conference in October 2016, and have been submitted as a peer-reviewed journal article (AlterNative, under review).

Snippets from the videos, with English sub-titles added, were also combined to create six short digital multimedia presentations on the mother-tongue foundations of successful community-based bilingual education:

1. Home is the Foundation
2. Family Leadership

3. Putting Inuktitut First
4. Learning by Hearing
5. Foundations for Literacy
6. Rich Environments

The six multimedia presentations are being released through the Akuttujuuk channel on isuma.tv, YouTube, and the Akuttujuuk website (e.g., http://akuttujuuk.ca/bilingual-learning-modules/rich-language-environments/). They are intended for further use by families, schools, DEAs, etc., and for viewing by Inuit across Inuit Nunangat. They can be used on a standalone basis or integrated into a single presentation as they were for a session on bilingual education to be used by the Coalition of DEAs.

This smaller scale, intensive, and mainly in-person collaboration was a successful example of Inuit educational leaders being empowered to generate, interpret, and disseminate knowledge about bilingual education. The Inuit research leader, Nunia, owned this part of the project and exercised a strong voice conducting the interviews, interpreting the data, creating the videos, and preparing the co-authored journal article. She expressed satisfaction throughout the process, and pleasure at seeing the work come together in forms that will reach larger audiences.

The work is being disseminated in forms that maintain the voices of the Inuit educational leaders who participated. The journal article quotes them extensively (although in English translation). The video snippets are particularly effective in that audiences will see faces, gestures, and expressions, and hear the speakers using their own words in Inuktut. In these ways, video dissemination has emerged as an effective tool for amplifying the voices of Inuit educational leaders who wish to share perspectives and experiences in bilingual education, especially with other Inuit audiences.

In 2016, as the modules are released, we will be able to track and evaluate how frequently these modules are accessed, and whether they are indeed effective tools for Inuit receiving knowledge.

In 2016/2017, we hope to repeat this process with an Inuit educational leader from Nunavik.

Meetings and Workshops (Collaboration)

Although the Akuttujuuk network was designed with the expectation that its online capabilities would address the challenges of a small population scattered over the immense territory of Inuit Nunangat by minimizing travel, face-to-face meetings and workshops have contributed to planning, data gathering, analysis and dissemination, and production of bilingual learning modules. Wherever possible, face-to-face meetings have been designed to address multiple purposes:

- Presentations and team meetings at NS@30: A Conference to Celebrate Innovation in Inuit and Indigenous Postsecondary Education, Gatineau, QC.
- Data gathering for “What Works in Bilingual Education?”, a set of knowledge mobilization/synthesis learning modules about bilingual education in Arviat, NU, supported in collaboration with the Nunavut Coalition of District Education Authorities (DEAs).
- Researchers and members meeting at the ArcticNet ASM in Vancouver in December, 2015.
- Preliminary data analysis and production work for the six videos and learning modules to support “What Works in Bilingual Education?” held in Winnipeg, MB.
- Online facilitators workshop/planning session and video interview with Dr. Jim Cummins, world-renowned expert on bilingual education, on the topic of successful bilingual education in Indigenous contexts to support a future learning module held in Toronto, ON.

Joint attendance at conferences, with time to work on presentations together before the date, has been an effective tool for amplifying Inuit educational leaders' voices as international scholars. At NS@30, Inuit educational leader and network member Jukeepa Hainnu was lead presenter on an analysis of the impacts of Inuit leadership on decolonizing bilingual education. Network members Naullaq Arnaquq and Becky Tootoo presented single-authored papers on Inuit language policies and Inuit cultural learning. As these women are busy educators and leaders with full-time jobs outside of academia, the partnerships with a university-based team are helpful for navigating processes of abstract submission, travel arrangements, conference registration, etc. The presence of these Inuit scholars at these meetings is of crucial importance for continuing to create spaces where Inuit see other Inuit as scholars generating and communicating new understandings based on academic research.

These in-person meetings have been important for establishing and maintaining the relationships that are at the core of Indigenous methodologies (Smith, 1999). Through formal meetings and informal meals together, we have continued to build the trust necessary for collaborative and empowering work.

The in-person meetings at conferences have also allowed for establishing new relationships which will support network expansion into other areas. For example, we have met with Jodie Lane, Nunatsiavut representative on the National Committee on Inuit Education, at each ArcticNet ASM, as well as the NS@30 conference. We have interviewed her as an Inuit educational leader, and her perspectives on bilingual education in Nunatsiavut are incorporated into Network deliverables.

An in-person meeting is planned for October 2016 at the Inuit Studies Conference in St. John's Newfoundland, co-hosted by the Nunatsiavut Government. At this point we hope to collaborate with Nunatsiavut colleagues for Nunatsiavut-specific deliverables.

Syntheses

As identified above, the knowledge synthesis has four main axes: analysis of existing qualitative data sets; compilation of existing research; literature review; and critical discourse analysis.

Qualitative Data Sets

As our work aims to amplify Inuit voices, our syntheses are grounded in Inuit narrative. Analysis of prior interviews, and interviews conducted as part of this research, led to the following priority themes being identified for further investigation: goals of bilingual education; context of bilingual education in Inuit Nunangat; promising practices in bilingual education; building teacher capacity; materials for teaching in a bilingual program; language policy; language loss, learning and preservation; beliefs about bilingualism and bilingual language acquisition; pride, identity, and shame; power relations, inequality, and the desire to find balance. The analyses of Inuit testimonies around each of these themes, currently coded and categorized using NVivo software for qualitative analysis, laid the groundwork for comparing and contrasting Inuit perspectives and knowledge with the knowledge coming out of the literature review.

Compilation of Existing Sources

In addition to asking under which conditions Inuit educational leaders are empowered to generate and disseminate understandings about bilingual education, we were also concerned with exploring practices which facilitate Inuit educational leaders accessing and evaluating published research about bilingual education. As part of this, we created an online, interactive library of publications using Zotero (Akuttujuuk Inuit Bilingual Education). The group library containing 459 sources, with full bibliographic references, abstracts or summaries, researcher's notes, and full text or links to full text as available (https://www.zotero.org/groups/akuttujuukinuit_educators_research_network). The group is private to allow for sharing of full-text sources, but anyone can find the group online and request to join. To date, only the two researchers actively involved in the literature review component of the project have been active users of the online group library.

Based on a sub-set of the Zotero group library, we also created a bibliography of 318 sources relevant to bilingual education in Inuit Nunangat. The sources are divided by region: NWT (19 sources), Nunavut (75 sources); Nunavik (58 sources); Nunatsiavut (16 sources); Urban Inuit (2 sources); Alaska (14 sources); Greenland (3 sources); multiple regions (29 sources); other Indigenous contexts (45 sources); theoretical sources (57 sources). Within Canada, we believe the bibliography is close to exhaustive. The dominance of sources from Nunavut and Nunavik, and the low number of sources representing work in the Inuvialuit Settlement Region and Nunatsiavut is representative of actual work/research relevant to bilingual education that has been completed in those regions. Sources from Alaska, Greenland, and other Indigenous contexts are samples of the work done there, and not intended to be an exhaustive list.

One idea for increasing Network members' engagement with the academic literature is posting lay summaries of different articles, particularly those by Inuit and Indigenous authors, in the Akuttujuuk blog.

An analysis of the authorship of the 216 sources identified specific to Inuit bilingual education shows that (to our best knowledge), 30 of the sources are single-authored by Inuit authors, and 24 were co-authored by Inuit and non-Inuit authors. The single-authored papers include Inuit graduate theses (e.g., Andersen, 2009); Inuit student research completed during Inuit-specific post-graduate programs and compiled by program instructors in edited volumes (e.g., Arnaquq, 2015; Qanatsiaq Anoee, 2015; Kauki, 2015; and other chapters in Walton and O'Leary, 2015); reports from Inuit organizations (e.g., Avataq, 2012; Inuit Circumpolar Council, 2008; Nunavut Tunngavik Incorporated, 2010; Torngâsok Cultural Centre, 2012); single-authored magazine or journal articles by Inuit (or Yup'ik) educational leaders (e.g., Annahatak, 1994; Charles, 2008; Nungak, 2014) and speeches by Inuit leaders acting in official capacities (e.g., Cournoyea, 2014; Simons, 2012).

Co-authored publications include journal articles, research reports, and documentary videos produced with university-based researchers, based on projects that were either initiated in communities, with academic support, or in which university-based researchers initiated community partnerships. Sometimes the line between these two cases is not clear. Examples include, in the Inuvialuit Settlement Region, Berger et al. (2016); in Nunavut, Arnaquq et al. (2013), Tulloch et al. (2009), and Walton et al. (2014); in Nunavik, Crago et al. (1993), De la Sablonnière et al. (2011), and Usborne et al. (2009), and in Nunatsiavut, Andersen and Johns (2005), Gatbonton et al. (2010), and Hackett et al. (2016). The Kativik School Board has been a leader in Inuit-driven, academic-partnered research in ways that do not show up in this list, as what we consider co-authorship based on co-creation of the knowledge being reported is sometimes recognized instead in acknowledgements or article texts (e.g. Kativik School Board, 1998; Taylor and Wright, 1995, 2003).

These results support a few conclusions about the circumstances in which Inuit educational leaders are empowered to generate and communicate knowledge about effective bilingual education in Inuit Nunangat. Single authorship appears to be facilitated by working beside and with the close support of a cohort of other learners and instructors (publications based on masters work), by publishing as an organization (where individual voices are not named), and by publishing/speaking in official, empowered leadership roles (e.g. Mary Simon as President of the National Committee on Inuit Education). University-community partnerships also appear to be effective strategies for incorporating Inuit voices within academic publications (in which leadership and the balance of Inuit vs. non-Inuit researcher is less clear).

Roughly one quarter of the sources specific to Inuit bilingual education have any Inuit authorship. In some ways, this number is encouraging as it reflects a strong increase from twenty years ago. However, it also shows that academic knowledge generation and dissemination about Inuit bilingual education continues to be dominated by non-Inuit researchers' voices.

Literature Review

A critical review literature has been conducted to synthesize current research, policies, practices, and beliefs about bilingual education in Indigenous communities, as relevant to Inuit contexts. The review draws on both narrative voice (interviews, stories, etc.) and academic literature (articles, reports, etc.), with particular attention to the works of Indigenous scholars, educators and writers as well as non-Indigenous researchers and scholars who have worked in Indigenous communities and have connections to community. The review included land claims, legislation and policy documents from the four regions, and ITK/Amaujaq National Centre for Inuit Education; theoretical papers summarizing large numbers of case studies and large scale quantitative studies; as well as case studies in Inuit Nunangat (Inuvialuit region, Nunatsiavut, Nunavik, and Nunavut), and comparable Indigenous settings, such as Hawaii and the Navajo nation in the United States; Maori in Aotearoa/New Zealand; Indigenous education in Australia; and other circumpolar Indigenous groups in Alaska, Greenland/Kalaallit Nunaat and Sápmi, with a view to sharing what can be learned in relation to experiences in Inuit Nunangat.

Deliverables related to the literature review include:

- A written literature review, created by Ph.D. student Cathy Lee, that will be included in her dissertation.
- A timeline of Inuit bilingual education from 1841 (beginning of Greenlandic Inuit language education) to present, posted on the Akuttujuuk website (http://akuttujuuk.ca/success-stories/a-timeline-of-inuit-bilingual-education/).
- A framework for effective bilingual education in Inuit Nunangat, posted on the Akuttujuuk website (http://akuttujuuk.ca/literature-review/)
- A series of blog posts addressing key issues in Inuit bilingual education, to be posted on Akuttujuuk website ("What is bilingual education?" "Why bilingual education?").
- A peer-reviewed article in which a previously-documented success story is re-interpreted applying theories from the literature review ("Transformational bilingual learning", submitted to Modern Language Review).

Key understandings emerging from the review include:

- Colonization has interrupted and blocked the transmission of Inuit Qaujimajatuqangit (Inuit ways), including intergenerational transmission of the Inuit language (Qikiqtani Inuit Association 2010; Rowan, 2014; Tagalik, 2010). The interruption of intergenerational transmission of Inuktut happened earlier in the most westerly and easterly Inuit communities (Patrick and Shearwood, 1999). The crucial role of parents as children's primary educators was deliberately undermined by the residential schools, with ongoing effects on language learning and educational outcomes (TRC, 2015). Ongoing implicit colonizing practices (TRC, 2015) need to be halted, and parents' inherent leadership role restored (Smith, 1995) in order to establish stronger foundations for effective bilingual education in Inuit Nunangat (Aylward, 2007, 2009; Berger, 2009; Fyn, 2014; Salokangas and Parlee, 2009).
- All four Inuit regions in Canada have land claims agreements that create space for Inuit-driven action toward bilingual education. In Nunavik, the right to and mandate for Inuktut-language education is written straight into the land claim (James Bay Northern Quebec Agreement, 1975). In Nunatsiavut (2005) and Nunavut (1993),

the land claims established self-governments with authority over education, and affirmed the importance of Inuktut to Inuit. The Inuvialuit Final Agreement (1984) created the Inuvialuit Social Development Program to address ongoing Inuit-specific concerns in education and maintenance of traditional practices (among others).

- Language-of-instruction legislation and policies, where they exist, are also favourable to Inuktut language-of-instruction, at least from Kindergarten to Grade 3 (e.g. Kativik School Board Policy on languages of instruction, 2003; Northwest Territories *Education Act*, 1995; Northwest Territories Department of Education, Culture, and Employment Departmental Directive on Aboriginal language and culture-based education, 2004; Nunavut *Education Act*, 2008). Nunatsiavut government has not yet exercised its right to control its own education system. Protective measures in the land claims, laws, and policies are effective measures against repeating overtly assimilationist agendas (Hornberger, 2009).
- Actions of principals, teachers, parents, and students profoundly impact language-of-instruction practices in schools, sometimes in support of and sometimes counter to existing policies (Aylward, 2010; Lewthwaite, 2007; May et al., 2004; Wyman, 2004). The most effective implementation of true bilingual education occurs in schools with strong Inuit leaders or culturally-sensitive, long-term Northerners (Lewthwaite, 2007; Tulloch et al., in press; Walton et al., 2014).
- Engagement with parents is a core success factor, particularly when such engagement equips and empowers parents, and does not just treat them as servants of the school's agenda (Aylward, 2009; Simons, 2012; Taylor et al. 2014; Tuafuti and McCaffery, 2005).
- Training of Inuit teachers who are fluent in Inuktut, which began for Nunavik and the Northwest Territories (Nunavut) in 1967 (local programs, which are particularly necessary, started in 1979) is a core component of bilingual education (Cram, 1995; Patrick and Shearwood, 1999). Nunatsiavut is appropriately laying a foundation for Inuit-controlled education through teacher training with a strong language-learning component (Anderson and Moore, 2016). Nunavut, Nunavik, and Alaskan Yup'ik educators have had opportunities to participate in Inuit (Yup'ik)-specific post-graduate (M.Ed., Ph.D.) programs (Marlow and Siekmann, 2013; Wheatley et al. 2015). Ongoing specialized professional education is required to equip teachers to understand specific patterns and needs in emergent bilinguals' learning, to ensure cultural and linguistic sensitivity among teachers, and for Inuit teachers to obtain certifications required to access leadership positions (although certification in itself is not enough) (O'Donoghue, 1998).
- For many Inuit, bilingual education is synonymous with Inuit language preservation (Aylward, 2010). Parallel language reclamation initiatives support, and are supported by, bilingual education (Avataq, 2012; Cournoyea, 2014; Government of the Northwest Territories, Department of Education, Culture and Employment, 2013; Government of Nunavut, Department of Culture and Heritage, 2012; Torngâsok Cultural Centre, 2012). Successful implementation of bilingual education requires careful attention of the role of schools in language preservation as well as the role of schools in providing the best possible education through affirmation of students' home language and culture (Hacharek, 2003).
- Children's language skills, their cultural identity, their self-confidence and their overall achievement in school are developed through, enhanced and supported by bilingual education (NTI, 2000b; Tagalik, 2010; Taylor and Wright, 2003). Affirmation of identity is one of the most significant factors in Indigenous learners persistence and success (Cummins, 2000). Connectedness to culture also supports student

persistence through to post-secondary (Fuzessy, 1998). Research in the Kativik School Board consistently showed higher self esteem among children educated in Inuktut (Wright and Taylor, 1995). However, research in upper grades in Nunavut has shown that implicit, sometimes unintentional, colonizing discourses from non-Inuit teachers can threaten the affirmation of positive Inuit identities, even where official policies and practices are highly favourable (Berger, 2009). Incorporating translanguaging practices (Celic and Seltzer, 2011) could be one strategy for non-Inuit teachers who do not understand Inuktut to incorporate some Inuktut in their classrooms and communicate respect for Inuktut language and culture.

- To become able and skilled bilingually, students need long-term, ongoing opportunities to expand their proficiency in each language (called additive bilingualism). In every region, there are concerns about truncated competences (Blommaert et al. 2005), which is when an individual's level of language proficiency is insufficient to effectively participate in certain communicative practices. Literacy and print-rich environments in both languages are essential to promoting literacy practices in both languages. Indigenous literacies, including storytelling, songs, dances, etc. are meaningful ends in themselves, as well as effective bridges to other forms of literacy (Balanoff and Chambers, 2005; Parker Webster and John, 2013). "Students doing powerful things with language, with literacy, with both their languages from the earliest days of schooling" is essential to the success of bilingual learners (Cummins, Interview July 2015). Explicit teaching alongside rich exposure and opportunities for meaningful interaction is needed to gain academic language proficiencies (Figure 4 and Figure 5).

Further findings from the literature review may be read on the Akuttujuuk website.

The purpose of the literature review, in part, was to identify key texts that would be of interest to Inuit educational leaders, particularly those authored by Inuit scholars. One way we have tried to facilitate network members' access to the information in the literature is short reviews synthesizing main points for quick reading. In 2016/2017, we will also explore posting short lay summaries of particular texts to see if these pique network members' reading interest.

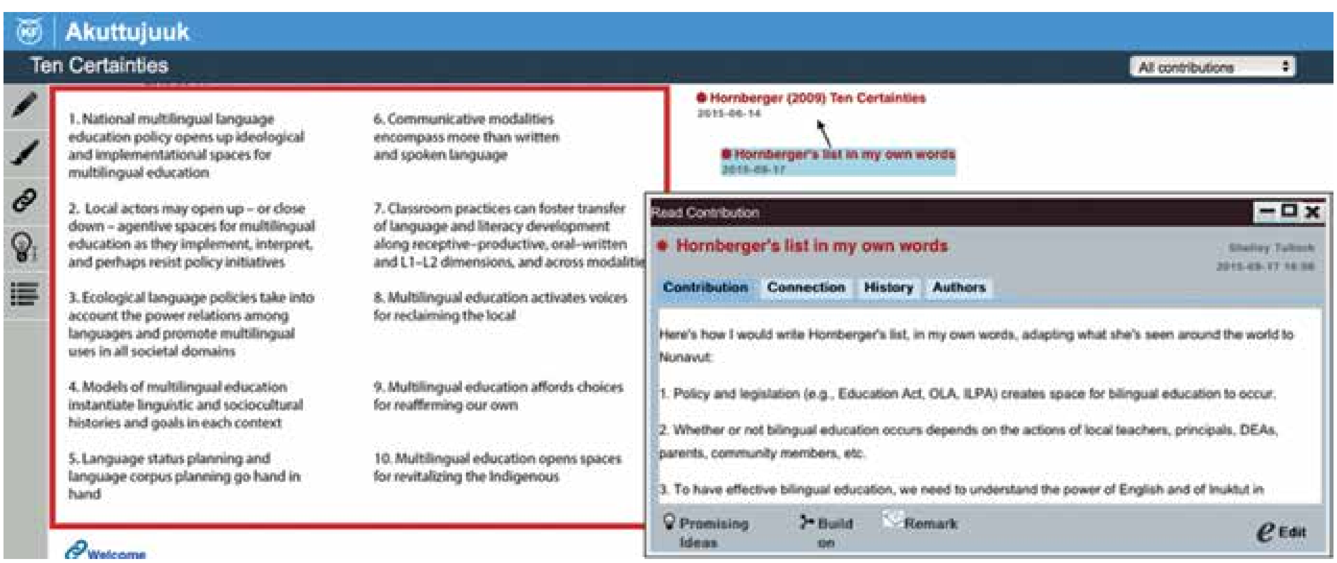

Figure 4. Example of knowledge synthesis from the literature review and data analysis.

Critical Discourse Analysis

Finally, the knowledge syntheses component of this project included critical discourse analysis (Johnson, 2011). Critical discourse analysis was used to assess the explicit and implicit messages, goals, and audiences of Inuit language-of-education policies from the four Inuit regions. It was also used as a tool for analyzing different language policy texts and their relation to prior and following discourse. Key findings to date include:

- Current processes and outcomes of bilingual education in Inuit Nunangat need to be understood in light of power relations, ideologies about language, bilingual learners, and education, as well as in light of the shifting bilingual context and history of schooling in the North.
- Public and professional discourse about bilingual discourse (e.g., among teachers, parents) reflects ongoing misunderstandings about the processes and outcomes of bilingual education (e.g., Special Committee to Review the *Education Act*, 2015).
- Parents, educators, and policy makers sometimes consider the multiple goals of bilingual education (effective learning; language reclamation; capable citizens) as in competition, when in fact research shows they are mutually supportive. In particular, the perception that teaching English earlier will necessarily lead to better English proficiency is widespread, but consistently contradicted in research that shows effective transfer of proficiencies from one language to another.
- Some language-in-education policy documents show clear and deliberate influence from community consultations and research, e.g Kativik School Board research and policy; Martin's (2000) and Corson's (2000) language-of-instruction papers that influenced the *Education Act*. Other language-in-education policy-related documents seem to go against research.
- New theoretical developments in the study of bilingual education between 2000-2015 are insufficiently represented in legislation, policy, and public discourse, although some teachers are intuitively implementing practices that such developments support.
- Changing and heterogenous language practices in homes, and lack of understanding in schools and on community committees of children's home language use creates additional challenges in establishing and implementing effective school language policies, particularly when discourse focuses on "mother tongue".

Figure 5. Excerpt from the learning module/presentation prepared for the Nunavut Coalition of DEAs.

Our critical discourse analysis is a work in progress. The methodology presents an additional tool for evaluating flow of ideas and knowledge about bilingual education in Inuit Nunangat, and the relative empowerment of Inuit as leaders and participants in discourse that leads to policy changes. We are drafting results for a peer-reviewed journal article, for submission to Language Policy in 2016.

DISCUSSION

Online Presence (Infrastructure)

Creation of an online presence for Akuttujuuk and the infrastructure to support both the presentation and dissemination of knowledge and practices as well as the co-construction and discussion of that knowledge has proceeded relatively well. Not surprisingly, the private Facebook group has been most used, possibly because it can be checked quickly as part of members' daily online activities. It has served primarily as a medium for sharing and as a springboard to other websites and resources or to more sustained and demanding work in Knowledge Forum. Perhaps because it requires an extra step to access and is being used for more sustained work, the Knowledge Forum database is seeing less traffic and relatively fewer contributions.

One of the more surprising statements from various network members has been their concern for privacy and a secure space in which they can feel free to express their thoughts without fear of censure or reprisal. While this need is met by the closed nature of Facebook and Knowledge Forum, it runs counter both to the goal of the network to facilitate sharing and discussion across Inuit Nunangat and the public spaces required to support that goal. This issue will have to be addressed in the coming year as it will be a major impediment to the utility of the Akuttujuuk website/blog and @Akuttujuuk Twitter feed.

Meetings and Workshops (Collaboration)

While the online supports have enabled Akuttujuuk members to maintain their connections without meeting face-to-face and have greatly increased the possibilities for sharing, face-to-face meetings have been essential for data collection and analysis, multimedia production, and dissemination. To some extent this may be due to the fact that Internet access across Nunavut, and perhaps even the entire Inuit Nunangat, is erratic at best, particularly with applications requiring high bandwidth. This means that online meetings via such things as videoconferencing are problematic and, consequently, the nuances of a face-to-face context are difficult to achieve. While the Akuttujuuk infrastructure used to this point has been selected because of its demonstrated reliability on low bandwidth, disseminating the learning modules and generating interactions around them from multiple sites simultaneously will allow us to test possibilities for alternatives to face-to-face meetings. Other alternatives to in-person data collection include the possibility of video generated at the community level, something which is also consistent with the co-construction of knowledge that lies at the heart of this project.

Syntheses

Production of the six modules on community-based bilingualism as practiced in Arviat has demonstrated the possibilities of integrating community practices and findings from the mainstream research into learning modules about bilingual education to be used by the Nunavut DEA Coalition in communities across the Territory. The modules may also be used as a basis for discussion and sharing with other regions and communities.

Compilation of published sources on Inuit bilingual education in a working bibliography, synthesis of these sources in a series of short, accessible documents, and critical analysis of the discourse contained in them, has established a solid foundation of what has been learned and studied to date concerning bilingual education in Inuit Nunangat.

The next task at this stage is to share these syntheses with a wider audience. We hope to structure further Inuit-driven discussion around them in order to ensure our syntheses accurately incorporate Inuit perspectives and local, expert knowledge, and thus stimulate a new form of synthesis.

CONCLUSION

The Akuttujuuk network was established to foster deeper understanding of what constitutes successful bilingual education and to identify how such programs may be adapted and implemented successfully across Inuit Nunangat to enhance the well-being and academic success of Inuit students. Building on the relationships established through the Nunavut MEd program between 2006 and 2013, the viability of the co-construction of knowledge through the collaboration of Inuit and non-Inuit sharing a common belief in the importance of bilingual education has been demonstrated. However, we have also demonstrated difficulties in Inuit educational leaders taking a strong voice as independent scholars of Inuit bilingual education. Gaps in Inuit educational leaders speaking powerfully into Inuit bilingual education policy and practice, as well as gaps in knowledge transfer between researchers, policy makers, and those implementing policies in families and schools, is leading, in some cases, to weak implementation of favourable, research-based policies. The online infrastructure established and tested over the last year of the research provides the means for extending the conversation and deepening the sharing. That will be the main task for the coming year.

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Housing, Health, and Well-Being Across the Arctic: Regional, Local, and Family Perspectives

Project Leaders

Mylene Riva (Université Laval); Christopher Fletcher (Université Laval)

Network Investigators

Jill Baumgartner (McGill University)
Trevor Bell (Memorial University of Newfoundland)
Gina Muckle (Université Laval)
Thierry Rodon (Université Laval)

Collaborators

Belkacem Abdous (Université Laval)
Ross Bailie (Menzies School of Public Health)
Alain Bellefeuille (Société d'Habitation du Québec)
Myriam Blais (Université Laval)
Tim Brown (Nunavut Housing Corporation)
Serge Déry (Nunavik Regional Board of Health and Social Services)
Sharon Edmunds-Potvin (Nunavut Tunngavik Incorporated)
Christina Goldhar (Memorial University of Newfoundland)
Gwen Healey (Qaujigiartiit Health Research Centre)
Linnea Ingebrigston (Nunavut Department of Health)
Amy Johnson (University of Alberta)
Faiz Ahmad Khan (McGill University)
Elena Labranche (Nunavik Regional Board of Health and Social Services)
Dick Menzies (McGill University)
Louise Potvin (Université de Montréal)
Rudy Riedlsperger (Memorial University of Newfoundland)
Tom Sheldon (Nunatsiavut Department of Lands and Natural Resources)
Fournier Watson (Kativik Municipal Housing Bureau)
Scott Weichenthal (McGill University)

HQP

Marie Baron, Doctoral Student (Centre de Recherche du Centre hospitalier de l'Université Laval)
Camille Pépin, Doctoral Student (Centre de Recherche du Centre hospitalier de l'Université Laval)
Philippe Dufresne, Research Associate (Centre de Recherche du Centre hospitalier de l'Université Laval)
Aurélie Maire, Research Associate (Centre de Recherche du Centre hospitalier de l'Université Laval)
Rachel Kohut, Undergraduate Student (McGill Faculty of Law)

ABSTRACT

Access to adequate housing has been a social, ecological, and health problem in Inuit communities since the movement toward sedentary living began in the 1950s. A large proportion of Inuit households live in inadequate housing conditions that contribute to the severity and the frequency of respiratory health problems, especially among children, infectious diseases, social and mental health problems in the Arctic. Studies have shown that “rehousing”, i.e. moving to a new dwelling, may improve health directly or indirectly through psychosocial pathways. The project brings together Inuit and Western epistemologies (ways of knowing) and methodologies (ways of doing) to assess the impacts of housing conditions on individual, family, and community health and well-being in Nunavut, Nunavik, and Nunatsiavut. This interdisciplinary project will study four inter-related components: 1) the health and well-being impacts of moving to a newly built social housing unit; 2) the experience of housing transitions on the lives of Inuit families moving into a) new social housing units in Nunavut and Nunavik; and b) an Inuit designed energy-efficient multiplex unit in Nunatsiavut; 3) the definition of adequate housing, overcrowding and its influence on health and well-being from Inuit perspectives; 4) the role of housing conditions for fostering and sustaining healthy ageing. For Component 1, all adults aged 18 years and older in single-person or family households on the waitlist for social housing will be invited to participate in survey interviews. Questionnaires will assess: housing conditions; mental and physical health, and stress; psychosocial factors; socioeconomic information; and health of children aged 3 to 36 months. In a subset of houses, indoor air quality and noise will be monitored during 24-hr. For Components 2, 3, and 4, qualitative methods employed will be conversation based. Specific methods include focus groups, individual interviews, visual methods (digital storytelling, photovoice, photo-elicitation) and community housing histories. These methods will be applied to explore participants housing conditions, experiences during their housing transition, their overall sense of health and wellness, meanings of home and of adequate housing, ageing in the home; participants will be invited to tell stories and share experiences. This project was developed through ongoing collaboration between university researchers, Inuit/northern researchers, and Inuit partners/organizations. Assessing the health and wellbeing impacts of moving to a new house is timely as all regions are currently restructuring their long-term housing strategies. Identifying housing conditions (perceived and objective) and psychosocial factors influencing health and well-being could suggest points of interventions and facilitate the targeting of housing resources more effectively. Qualitative descriptive and thematic work will help identify specific pathways to health and illness associated with housing while also developing indicators and models that are relevant to, and draw form, Inuit culture and historical experience. This type of project has been identified as required to build effective evidence-based cases justifying greater investments in affordable housing in the Arctic.

KEY MESSAGES

- Poor housing conditions, including overcrowding, have wide-ranging health and social impacts. Population Health Intervention Research (PHIR) has shown that moving to a new house may improve health directly or indirectly through psychosocial pathways. To date only one study has assessed the impacts of moving to a new house on health improvements in Indigenous communities (among Aboriginals in Australia), and none among the Inuit.
- We designed a pre-post survey to assess the impacts of moving to a new house on mental health, stress, and physical health and the mediating role of psychosocial factors (PSF) in six communities in Nunavik and in six communities in Nunavut.

- The survey is additionally supported by a PHIR grant from the Canadian Institutes of Health Research.
- At baseline, we recruited 134 participants in Nunavik (October-November 2014) and 155 participants in Nunavut (May-June 2015). Of these participants, 186 moved to a new house (64%).
- Preliminary analysis of baseline data indicates that 51% and 65% of participants lived in overcrowded dwellings in Nunavik and Nunavut, respectively. There is good agreement between objective and perceived measures of crowding.
- Follow-up data collection will be conducted about 18 months after participants moved into a new house: in May-June 2016 in Nunavik and in Oct-Nov 2016 in Nunavut.
- In the upcoming months, additional projects will be conducted to:
    a. Measure indoor air quality in Nain, Nunatsiavut (2016);
    b. Understand Inuit families' experience of housing transitions into new social housing units (2016) and an Inuit-designed multiplex unit (2016 and 2017);
    c. Understand cultural practices and meanings of adequate housing and overcrowding (2017); and
    d. Explore the role of housing in fostering healthy aging (2017).

OBJECTIVES

Our project "Housing, health, and well-being across the Arctic: Regional, local, and family perspectives" (hereafter Housing and Health in the Arctic) consists of five interrelated components, each with specific objectives:

1. Assess the impacts of moving to a newly built social housing unit on Inuit health and well-being, and the mediating role of PSF;
2. Assessing indoor air quality (pilot project);
3. Document the experience of housing transitions on the lives of Inuit families moving into a) new social housing units in Nunavut and Nunavik and b) an Inuit-designed multiplex unit in Nunatsiavut;
4. Define adequate housing and overcrowding and their influences on health and well-being from Inuit perspectives;
5. Assess the role of housing conditions in fostering and sustaining healthy aging in the Arctic.

In the first year, activities were conducted to realize Objective 1 only. Preliminary activities were conducted for Objective 2. This section of the report will focus only on research activities related to Objective 1. Initially, fieldwork for Objectives 2 and 3b were supposed to be realized in Year 1, but because of logistics issues and delays in housing construction they have been postponed to Year 2, 2016-2017; we explain reasons for this situation more fully in the section Overview of work for 2016-2017. Objective 3a is still planned for 2016-2017, whereas the schedule for Objectives 4 and 5 has not changed and is still planned for 2017-2018.

INTRODUCTION

In 2006, 39% and 49% of the population in Nunavut and Nunavik respectively reported living in overcrowded houses, vs. 3% of non-Indigenous Canadians.[1] Living in houses requiring major repairs was reported by 26% and 46% of the population in Nunavut and Nunavik respectively, vs. 7% of non-Indigenous Canadians. In the Arctic, pressures for the construction of new housing is exacerbated by the young and rapidly growing population (e.g. in Nunavik, half of the population is < 25 years; 25%

population increased from 1996-2006, compared to 8% for Quebec),[1] the short construction season and high cost of materials. In 2010, a backlog of about 1000 housing units was estimated for Nunavik alone.[2] Since the imposition of settlement living in the 1950's and history of environmental dispossession, overcrowding and poor quality housing have become commonplace in many Indigenous communities in Canada. Housing conditions are a key determinant of health.[3-5] The housing shortage and poor housing quality in the Arctic are compromising people's health and communities' capacities for social and economic development.[6]

Population Health Intervention Research (PHIR) has shown that moving to a new house may improve health directly or indirectly through psychosocial pathways.[7, 8] To date, few studies have assessed moving to a new house in relation to health improvements in Indigenous communities,[9] and none among the Inuit. In 2014-2015, 216 public housing units were constructed in eight (out of 14) communities in Nunavik; 210 housing units were built in 12 (out of 25) communities in Nunavut. In collaboration with Inuit organizations responsible for housing, public health and social services, we designed a study to assess the impacts of moving to a newly built social housing unit on health and well-being of Inuit households in Nunavik and Nunavut.

Housing conditions and health

A large body of evidence indicates strong, mostly cross-sectional, associations between poor housing and poor health .[10, 11] This research is however mostly based on non-Indigenous populations. The literature synthesized below presents results of selected studies, with a particular focus on studies conducted among Indigenous populations.

Physical health: Among Indigenous populations, research on housing conditions has mainly focused on respiratory health, especially among children [12-14], and on high rates (and transmission) of TB.[15] For example, the prevalence of lower respiratory tract infection (LRTI) and hospitalizations due to LRTI is significantly higher among Inuit infants and children living in more densely populated households in Canada,[12, 13] Alaska,[16] and Greenland.[17] An ecological study showed increased TB incidence in First Nations communities in Canada characterized by higher household crowding.[15] In Australia, household overcrowding has been associated with the development of ear infections in Indigenous children, potentially compromising their development and school achievement.[18] There is strong and consistent scientific evidence that adverse indoor environmental quality is harmful to human health.[19] Indoor environments can be contaminated by chemical, organic, and particulate matter pollutants such as environmental tobacco smoke. Exposure to mold and bacteria and their components also impact human health.[20] Exposure to environmental tobacco smoke was identified as a risk factor explaining increased risk of lower respiratory tract infections among young children.[13] There is also sufficient scientific evidence that noise exposure, both indoors and outdoors, can induce a range of adverse health outcomes including hearing impairment, hypertension and ischemic heart disease.[21]

Mental health: Household overcrowding has been associated with poorer psychological well-being in several studies with cross-cultural samples.[22-24] Sex-specific differences in mental health in response to living in crowded households have also been reported.[25, 26] For example, Regoeczi showed that women living in more crowded dwellings were more likely to be depressed, whereas men reported higher levels of withdrawal.[27] Among Greenlandic Inuit, a recent study shows higher prevalence of poorer mental well-being in crowded households, especially among women.[28] Research further suggests that housing type, i.e. multi-dwelling housing is associated with adverse psychological health.[22]

Noise within and outside the house is associated with annoyance and sleep disturbance.[21] Among children, household crowding is associated with development [29, 30] and success in school.[31] A report from the Commission des droits de la personne et des droits de la jeunesse in Quebec identified housing conditions as a prerequisite for child well-being in Nunavik.[32]

Stress: A growing body of evidence suggests that household crowding may be a chronic environmental stressor, eliciting physiological stress responses.[33-35] Household crowding has been associated with increased blood pressure among boys in India,[36] and with the incidence of hypertension among Caucasian American women.[37] We recently examined the association between household crowding and chronic stress among Inuit in Nunavik; results of our study showed elevated stress levels among adults living in overcrowded households, and especially among women, independently of individuals' characteristics.[38]

Health impacts of housing interventions

Results of systematic reviews of studies assessing the health impacts of housing interventions such as moving to a new house[11] report overall positive health impacts, but these do not always reach statistical significance. A recent Cochrane review of housing interventions identified 14 studies (with a wide range of study designs) examining the health impacts of moving to a new house published since 1995.[11] Among studies reporting significant health impacts (n=5), some observed improvement in mental [39-41] and self-reported general health outcomes after moving to a new house [41] and improved mental health in association with improvement in housing conditions after the move.[7] Associations with respiratory health were mixed, although one study reported significant reduction in asthma and bronchial symptoms in adults.[42]

Studies assessing the health impacts of reduction in crowding and improvement in housing quality following moving to a new house are particularly relevant for this project. In a housing relocation program for low-income women, improvement in housing quality, and especially reduction in crowding, predicted improvement in post-move psychological distress.[40] Kearns et al. observed that gains in space and privacy, proxy measures of crowding, were significantly associated with improvements in health scores among families with dependent children.[7] The Housing Infrastructure and Child Health Study set in 10 Indigenous communities in Australia assessed whether moving to a newly built dwelling was associated with improvements in housing infrastructure including a reduction in overcrowding, and with improvement in children's physical health.[9] In this study, moving to a new house was only marginally associated with a reduction in crowding and there was no consistent reduction in childhood illnesses in relation to housing improvements. The authors suggested that building/moving to a new house programs alone may have limited potential to improve health, especially in communities with high levels of overcrowding, arguing for the need for such programs to be supported by social, behavioral and community-wide environmental interventions to more fully realize their potential for health improvements.[9]

Psychosocial factors as pathways between housing and health

One possible explanation for conflicting evidence of the health impacts of housing intervention studies is that conventional mental and physical health scales might not be the ideal measures for capturing benefits specific to housing interventions.[8] Despite attempts to conceptualize the pathways through which housing conditions influence health,[43] many of these studies treat the health impacts of housing improvements as a 'black box', comparing health before and after the intervention.[8] Yet a growing literature suggests that housing conditions might influence health through psychosocial pathways. The term 'psychosocial' refers to the influence of social factors on an individual's mind or behavior, and to the interrelation between mind/behavior and social factors.[44] Housing studies have examined a range of PSF, including: control and powerlessness, with consequences for self-efficacy;[22, 45, 46] identity and self-esteem;[22, 46] risk and insecurity, with consequences for anxiety and fear;[22] lack of privacy and reduced neighborliness;[46] satisfaction with the house;[43] and social support.[40, 47] For example, in crowded dwellings, the lack of privacy and the impossibility of withdrawing from social interactions limits the ability of controlling one's home situation,[48] possibly eliciting ill-health. Years of research on PSF in the workplace show that low control and high demand are associated with increased cardiovascular morbidity among men.[49] Studies have demonstrated that, among women, low control at home significantly predicted anxiety and depression [50] and coronary heart diseases.[51] A recent study provides further evidence of the mediating effects of PSF on health improvements following moving to a new house.[7, 52] One year after moving to a new house into newly constructed social dwellings, changes in self-reported PSF, e.g. feelings of control, identity, status, and privacy within the home, were greater than changes in mental well-being.[52] Two years after moving to a new house, improvements in mental well-being were mostly due to changes in PSF.[7] With respect to macro-level PSF relating to community-level conditions, evidence from 'neighborhood and health' research shows that neighborhood conditions such as perceived social cohesion, social capital, collective-efficacy, and security are associated with physical and mental health outcomes, independently of individuals socioeconomic characteristics and meso-level PSF.[53, 54]

There are few studies on housing conditions and PSF or PSF and health among Inuit and Indigenous populations. However, studies have discussed the design of the 'euro-Canadian' house in the Arctic as not conducive for traditional lifestyles and not reflecting cultural identity,[55] and crowding in relation to social problems.[56] The cultural relevance of indicators of crowding, such as the person per room (PPR) and the National Occupancy Standard (NOS), has been questioned for research among Indigenous populations,[57, 58] suggesting that subjective experience of crowding might be a more culturally appropriate measure.[56, 58] Finally, social support is identified as an important determinant of Indigenous thriving health,[59] including mental health among Inuit.[28]

Description of the housing intervention under study

The housing intervention studied in this project is the allocation of newly built social housing units to households on the waitlist for social housing in Nunavik and Nunavut. The primary objective of this intervention is to improve living conditions by alleviating crowding and providing good quality housing. This intervention is thus a 'natural experiment', i.e. an intervention for which the research team does not control the allocation to particular communities/individuals (nor the planning or financing), but where predetermined variation in allocation occurs.[60] Changes in health are not the intended outcome of the intervention, but rather constitute 'spillover' effects.[60, 61]

In the Canadian Arctic, the housing market is largely subsidized, with close to 60% of the population in Nunavut [62] and over 90% in Nunavik[1] living in social housing. In Nunavut, the primary homebuilder is the Government of Nunavut through the Nunavut Housing Corporation (NHC) who is the sole owner of social housing units. Nunavut still receives funding from the Federal Government.[63] Tenants rent their house from the NHC through Local Housing Organizations. In Nunavik, social housing is financed by Société d'Habitation du Québec (SHQ) (with no direct investments from the Federal Government), and Makivik Corporation, through its construction division, is the main homebuilder. Once housing units are built, Kativik Municipal Housing Bureau (KMHB) becomes the sole owner with responsibilities for their administration and maintenance. In both regions, new housing units are first allocated to communities where the housing shortage is most acute. They are then allocated locally to applicants most in need, where need is defined by a point-based system set according to specific criteria, lower-income, dependent children, living in overcrowded dwellings. In Nunavut, tenants pay monthly rent on a geared-to-income basis. In Nunavik, rent is calculated according to a formula that considers house size and income. Living in social housing in these regions is thus not a marker of socioeconomic status as observed in non-Indigenous populations,[43] as most people live in social housing independently of their income levels.

In 2014-2015, 216 public housing units were built in eight (out of 14) communities in Nunavik and 210 housing units were built in 12 (out of 25) communities in Nunavut. Construction included a mix of one-bedroom, two-bedroom, and four-bedroom dwellings, accommodating single-person households and small and large lone-parent or two-parent family households with dependent children.

The **overall aim** of this project is to assess the impacts of moving to a new house on mental health, stress, general and physical health and the mediating role of PSF. **Specific research objectives** are to:

1. Examine whether moving to a new house is associated with changes in: a) crowding and housing quality, b) health, and c) PSF.
2. Examine whether changes in crowding and housing quality are associated with changes in a) health and b) PSF.
3. Examine whether the association between changes in housing conditions and changes in health are mediated by PSF.

It is hypothesized that moving to a new house - by reducing exposure to overcrowding and improving housing quality - will be associated with better health directly, and indirectly through changes in PSF.

ACTIVITIES

Study design and sample size

The project uses a prospective study design with assessments before and after moving to a new house. Baseline data was collected one to four months before participants moved to a new house, i.e. in the Fall 2014 in Nunavik, and in Spring 2015 in Nunavut; follow-up data collection will take place 15 to 18 months after the move. This time to follow-up will be longer than housing intervention studies[11] and should provide enough time to observe changes in PSF and in health.[52]

Households on the waitlist for social housing were recruited in six communities in Nunavik and six communities in Nunavut where new social housing units were built in 2014 and 2015. Households on the top of the wait list for social housing, i.e. those who are most likely to move, were recruited by local housing officers (LHO). To account for the fact that not everyone met at baseline would actually get to move to a new house (as rank on the wait list may change between baseline interview and housing allocation), households in each community were oversampled by 25%.

Data collection

In each community, a team of two research assistants (RAs) collected data. They were assisted by one local Inuit researcher (IR) who helped with contacting participants, scheduling interviews, and assisting with administering questionnaires in Inuktitut or Inuinnaqtun when requested by participants. Data collection took place in a neutral environment (e.g. rented room at the municipal office). Two questionnaires were used to collect data at baseline and follow-up. The household questionnaire was administered to the person whose name was on the waitlist; only one person per household responded to this questionnaire. All participants responded to the individual questionnaire. The questionnaires were developed in collaboration with Inuit partner organizations. They were pilot-tested with Inuit living in Quebec City, Nunavik and Nunavut.

Household Questionnaire: Within the household, people reported the number of rooms, bedrooms, and occupants, broken down by age and sex. From this information, different indicators of overcrowding were computed, including the person per room (PPR) indicator used by Statistics Canada.[64, 65] Housing quality is assessed using questions and scored on Likert scales on housing type and design, available amenities, maintenance, and smoking restriction.[56, 66] A housing quality score is composed from these variables.[8] Questions on housing quality have been used in other Inuit/Indigenous surveys in Canada[56, 67] and previously developed in collaboration with partner organizations and pilot-tested in Nunavik.[68]

Individual Questionnaire: Most questions employed in this questionnaire to assess health and well-being have been previously used in the Nunavik Inuit Health Survey (NIHS)[69], the International Polar Year – Inuit Health Survey (IPY-IHS)[70], and the Nunavik Child Development Study[71], except when specified.

A. Health-related questions:

- *Psychological distress.* Assessed using the six-item K6 scale.[72, 73] The K6 is a very brief screening instrument for depression and other common mental disorders, with validity established in the general population.[72-74]
- *Perceived stress*. Level of stress perceived in the past month was measured using the 10-item Perceived Stress Scale.[75] The PSS is one of the more common noninvasive measures of subjective stress in psychophysical health research and has been used in cross-cultural samples.[76]
- *Major life events*. The Holmes and Rahe Stress Scale was reduced and adapted to account for other events that could explain levels of psychological distress and stress of participants, and confound association between housing conditions, and change in housing conditions, and mental health.
- *Physical health*
  - » *General health*, including:
    a. Self-rated health: this variable is predictive of morbidity and mortality[77] and is associated with clinically relevant indicators of risks for chronic disease among Inuit.[78]
    b. Perceived changes in health over the past year.
  - » *Respiratory symptoms/health* measurements were adapted from various survey instruments including the Confronting Chronic Obstructive Pulmonary Disease [79] and the European Community Respiratory Health Survey [80, 81] which have been validated against clinical measures.[81, 82]
  - » *Injuries in the home*
- *Additional measures*
  - » *Health of children aged between 3 and 36 months*. General health, respiratory health, ear infections and injuries in the home were assessed as secondary health outcomes.
  - » *Food security* is measured using the Household Food Insecurity Access Scale developed by the Food and Nutrition Technical Assistance (USA), with the formulation of questions more appropriate to assess food security among indigenous populations. This specific scale has recently been used to assess food security in Nunavik.

B. Psychosocial factors:

- *Psychosocial 'benefits' of the house.* A scale-based measure of psychosocial benefits was created by adapting items from Kearns et al.[7] and Dunn's studies[45] to measure: control; security and safety; privacy and retreat; identity and pride. Items are scored on Likert scales, and summed into an overall score. Higher scores indicate more psychosocial benefits from the house. Perceived household crowding [56, 58] and satisfaction with the house[43] are also assessed.
- *Community and neighborhood psychosocial environment* are assessed using items referring to belonging, social cohesion, safety, collective efficacy, accessibility of amenities, neighborliness. These items were adapted from existing studies (e.g. [7]), scored on Likert scales,

and summed into an overall score of community/neighborhood psychosocial environment.

- *Mastery*. Pearlin Mastery Scale is used to measure an individual's level of mastery, which is a psychological resource that has been defined as "the extent to which one regards one's life-chances as being under one's own control in contrast to being fatalistically ruled". This scale has been used in Indigenous health surveys across Canada (e.g. First Nations Regional Health Survey).
- *Social support and participation*. Personal social support is measured using 6 variables, scored on 5-point scale.[69, 83]

C. Behavioral and socio-economic information:

- *Behavioral risk factors* (smoking and alcohol consumption).
- *Sleep disturbance* in the previous month will be considered as mediating variable between housing conditions, e.g. noise in overcrowded households, and health outcomes.[84, 85] The 4-items Brief Sleep Disturbance Scale is used.[86]
- *Socioeconomic information* (marital status, socioeconomic status (income, employment, education), and caring for people with mobility/health problems).
- *Traditional lifestyles and activities* (e.g. involvement in traditional activities such as hunting, fishing, berry picking, crafts, going camping) as measures of 'cultural continuity' have been shown to be protective for Indigenous health[87, 88]).

Data analysis

- Descriptive statistics and frequencies for all variables have been produced.
- The internal consistency of scale-based variables has been examined in preliminary analysis (e.g. psychological distress, PSF, perceived community/neighborhood conditions, etc.)
- Chi-square analysis has been conducted to examine whether PSF vary between participants living in overcrowded vs. not overcrowded houses.
- Preliminary regression analysis (not presented in this report) has been conducted to examine associations between housing conditions and health outcomes.

Knowledge transfer and dissemination activities

Presentations at conferences:

- Riva, M., Fletcher, C., Dufresne, P. Structural, psychosocial, and spatial dimensions of housing in the Arctic. ArcticNet 11th Annual Scientific Meeting. Vancouver, December 2015.
- Riva, M. Projet d'évaluation des impacts sur la santé de l'accès à un nouveau logement. Journées Annuelles de Santé Publique. Montréal. December 2015.
- Riva, M. Psychosocial factors linking housing to health and well-being in the Arctic. Global environmental health: From Cell to society. McGill University. October 2015.

Scientific papers in preparation

- Riva, M., Fletcher, C., Dufresne, P., et al. Housing in the Canadian Arctic: assessing the impacts of moving to a new house for Inuit health and well-being. To be submitted to the International Journal of Circumpolar Health.
- Riva, M., Dufresne, P., Fletcher, C., et al. Housing in the Canadian Arctic: structural, psychosocial and spatial dimensions. To be submitted to Canadian Journal of Public Health.

Knowledge transfer activities with partners

- In March 2016, 2-day meetings will be held in Iqaluit and Kuujjuaq with partner organizations to analyze and interpret results of baseline data collection; to discuss the production of one-pager research reports of baseline data; and prepare the follow-up data collection.

RESULTS

A total of 289 adults were recruited at baseline (134 in Nunavik; 155 in Nunavut), for a response rate of approximately 68%. Of these, 186 participants (64%) moved to a new house.

Preliminary analysis revealed important variations between Nunavik and Nunavut in housing conditions. More participating households from Nunavut reported their house to be in need of major repairs (44% vs. 29% for Nunavik); and overcrowded (65% vs. 51%).

Previous studies have critiqued the cultural relevance of indicators of crowding, such as the person per room (PPR) indicator for research among Indigenous populations,[57, 58] suggesting that subjective experience of crowding might be a more culturally appropriate measure.[56, 58] We examined whether objective crowding, measured by > 1 PPR, according to Statistics Canada definition of overcrowding, corresponded to people's perception of whether or not they lived in a crowded dwellings. Results showed that among people living in overcrowded dwellings, 97% in Nunavik and 78% in Nunavut perceived their house to be overcrowded. This indicates that objective measurement of overcrowding, such as PPR, has good sensitivity to detect actual situations of overcrowding.

Psychosocial factors (PSF) associated with the house environment were evaluated in the individual questionnaire through 21 questions. These questions were used to describe concepts such as perceived identity, control, privacy, satisfaction and safety.

One of the main hypotheses of this project is that housing improvements will influence health through psychosocial pathways. To preliminarily test this hypothesis using cross-sectional data, we examined whether selected PSF differed by overcrowding (see results in Table 4). Results indicate, overall, that people living in overcrowded dwelling reported significantly less favorable PSF, i.e. did not agree with the selected items reflecting concepts such as privacy, identity, control, satisfaction. Feeling safe did not vary by overcrowding. We computed a PSF score, using all 21 items. The PSF score was significantly lower in overcrowded dwellings.

DISCUSSION

The follow-up data will allow examining the relationship between changing housing conditions, reducing overcrowding and change in physical and mental health through psychosocial pathways. It will also contribute information to better assess the cultural relevance of objective measures of crowding, in relation to perceived crowding. This will be the topic of a scientific paper.

CONCLUSION

Objective 1 of the Housing and health in the Arctic project is well underway. Baseline data is fully collected. Preliminary results indicate that, among participants in this study, a high proportion lives in overcrowded dwellings, especially in Nunavut. Living in overcrowded dwellings is associated with lower psychosocial factors such as control and satisfaction with the house.

ACKNOWLEDGMENTS

This project evolves within a collaborative research environment, which advocates true partnerships between university researchers and partners as well as involving participative inquiry where partners work closely with researchers at all stages of the process. The structure of governance of this project therefore reflects this philosophy.

The overall structure of the project is composed of the principal investigator, the university co-researchers, the research coordinator, students

and research assistants, and Nunavut and Nunavik partner organizations. University researchers and the partner organizations are on equal footing as research priorities will be determined through discussion and will strive to obtain consensus.

We have established a process for dissemination and publication of research results, whereby all research results and knowledge generated by the project is presented, discussed and approved by the partner organizations, university researchers, and the Nunavik Nutrition and Health Committee before they are disseminated externally to the general public, including scientific publications and conferences.

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See end of Activities section for publications from this project.

Diarrheal Illness and Enteric Infections Among Young Children in Nunavik and Nunavut

Project Leaders

Cédric Yansouni (McGill University Health Centre - Research Institute); David Goldfarb (Children's & Women's Health Centre of British Columbia)

Collaborators

Neil Andersson (McGill University)
Maureen Baikie (Department of Health and Social Services (Iqaluit))
Marcel Behr (McGill University Health Centre - Research Institute)
Theresa Gyorkos (McGill University Health Centre - Research Institute)
Sherilee Harper (University of Guelph)
Benoit Lévesque (Centre de Recherche du Centre hospitalier de l'Université Laval)
Amber Miners (Qikiqtani General Hospital)
Momar Ndao (McGill University Health Centre - Research Institute)
Jean-François Proulx (Nunavik Regional Board of Health and Social Services)
Marek Smieja (McMaster University)
Karine Thivierge (Institut national de santé publique du Québec)
Mary Ellen Thomas (Nunavut Research Institute)

ABSTRACT

An unprecedented outbreak of severe parasitic diarrhea caused by *Cryptosporidium* species was identified in Nunavik (northern Quebec) in June 2013 and has since spread to several villages. The same parasite was recently also found in the Qikiqtani region of Nunavut. *Cryptosporidium* is usually considered to be a problem in tropical countries, so finding it in the Arctic is quite unexpected. This is important because it mostly affects young children and is linked with long-term harm in other populations (growth stunting and possibly cognitive delay). Chlorination of surface water does not kill *Cryptosporidium*, and no effective drug treatment is available in Canada. More broadly, little is currently known about the frequency of diarrheal disease in people living in the Canadian Arctic, but the conditions allowing for cryptosporidiosis also favor transmission of many other intestinal infections. The objective of this project is to define the magnitude of diarrheal infections in Arctic communities, to assess their impact on child growth and development, and to propose interventions for prevention. We expect that intestinal infections are an important cause of preventable serious illness in the North. We plan to look for harmful microbes in stool from preschool-age children in two large Arctic communities. Results from this study will be presented to parents and other community members. The information gained from this project will directly help communities to make policies that will prevent infectious diarrhea, and ultimately help children to reach their full potential.

KEY MESSAGES

- The recent recognition of widespread human cryptosporidiosis in Nunavik and Nunavut raises concern about possible long-term effects on growth and development of children in Inuit communities.
- Repeated enteric infections are thought to be highly prevalent in these regions, but very little is known about the spectrum of causative agents or whether this enteric disease burden has a negative impact on the developmental trajectory of affected Indigenous children.
- This project aims to quantify the burden of enteric infections of childhood, measure their impact on child growth and development, and will inform subsequent community-adapted interventions that will prevent enteric infections and help children reach their full potential.
- Conventional diagnostics are often not feasible in remote settings. Most of the remote Indigenous communities of northern Canada have little or no local access to conventional microbiology testing for infectious diseases.
- This deficit is thought to contribute to ongoing disease transmission and the very high rates of enteric infections, sexually transmitted infections, and tuberculosis found in these communities.
- This project aims to implement near-care rapid molecular diagnostics in existing health structures, and demonstrate their feasibility of use and added value in remote northern settings.

OBJECTIVES

The objectives of the project remain unchanged.

Overall objective: To improve the health of young children in Canadian Arctic communities in partnership with local health authorities and parents/guardians. This will be accomplished by quantifying the burden of enteric infections of childhood, measuring their impact on child growth and development, and will inform subsequent community-adapted interventions that will prevent enteric infections and help children reach their full potential.

<u>Specific aim 1</u>: Determine the incidence and prevalence of (i) intestinal infections and of (ii) diarrhea in terms of age, sex and seasonality.

Specific aim 2: Identify the infectious causes of the diarrhea using appropriate laboratory methods.

Specific aim 3: Estimate the effect of intestinal infections and/or diarrhea on growth (using growth indicators of height-for-age (stunting) and linear growth velocity).

INTRODUCTION

Challenging living conditions in Arctic communities cause myriad health concerns, among which infections figure prominently.[1] For example, infections are among the top three causes of Inuit infant death.[2, 3] Diarrheal diseases are of particular concern in the Arctic because conditions favouring their transmission are common, such as significant overcrowding[4], specific food practices, and frequent use of untreated surface water.[5] Globally, one in ten child deaths results from diarrheal disease in the first five years of life.[6] Repeated exposure to enteric pathogens has been strongly associated with functional and structural disruption of the intestinal mucosa, a process termed environmental enteropathy.[7] Enteropathy is believed to be an important cause of growth failure in children, and areas with the highest rates of enteropathy coincide with those having the highest rates of childhood diarrhea. Although short-lived diarrheal episodes (i.e. an isolated episode of three days or less) do not appear to affect long-term growth, prolonged diarrhea (i.e. lasting 14 days or more) is strongly associated with reduced linear growth velocity (ranging from slow growth, to reduced adult height, to stunting in severe cases).[8-11] Parasitic infections caused by species of *Giardia* and *Cryptosporidium* are among the most common causes of childhood diarrhea in areas with high rates of environmental enteropathy and linear growth delays.[12, 13] The presence of enteric parasites in asymptomatic children is also an independent predictor of growth delay.[14] Further, emerging evidence suggests enteric infections in young children (either symptomatic or asymptomatic) may have sustained effects not only on growth but also other aspects of development such as cognition.[15] Worryingly, these effects are exacerbated by food scarcity, which is reported by 24-46% of households surveyed in Nunavik and Nunatsiavut.[16]

Unfortunately, little is currently known about the epidemiology of diarrheal disease in people living in the Arctic. Recent survey data found the highest self-reported incidence of acute enteric illness in the developed world is in Northern Canada [17]. The Nunavik Inuit Health Survey 2004 of people from all 14 coastal villages found that 10% of people reported having diarrhea in the previous month.[18] Alas, this type of data is subject to recall bias, underestimates the incidence of enteric infections by only describing those with diarrhea, and provides no information on the etiologic spectrum of disease.

To address this void, our team retrospectively performed molecular testing of all stool specimens submitted to the Qikiqtani General Hospital in Iqaluit, Nunavut over an 18-month period. We found that many enteropathogens – particularly *Cryptosporidium* species - were not being detected by conventional testing procedures and therefore were not being reported to public health authorities.[19] In the same year (2013), an unprecedented outbreak of severe parasitic diarrhea caused by *Cryptosporidium* species was identified in Nunavik.[20] It built momentum rapidly, spreading from a single village to ten villages in its first six months. In the course of investigating this outbreak, it has become clear that intestinal parasites are highly prevalent in Nunavik, with nearly 30% of individuals submitting stool for microscopy diagnosed with a reportable parasitic infection during the outbreak. Given that the majority of people affected by the outbreak are young children and that enteropathogens are associated with linear growth delay and possibly impaired neurocognitive development, the implications of these findings are important for affected communities.[7, 21] The emergence of *Cryptosporidium* in Arctic communities in Nunavik and Nunavut demonstrates a pressing need to investigate its epidemiology, which likely differs in several respects with previously described outbreaks in southern regions because of differences in customs, water infrastructure, and Arctic ecology.

ACTIVITIES

Time frame: April 2015 to January 2016

Research: The post-award period focused on planning study logistics, solving problems in the planned Nunavik study site, solidifying partnerships with northern colleagues, and intensively seeking outside funding partners to ensure the feasibility of the project as described.

1. Implementing results of the Research Agenda meeting:
   - We organized a CIHR-funded planning meeting "Building an Arctic Enteric Infections Research Agenda" in Iqaluit 22-23 March 2015 with clinicians, public health actors, and northern community members.
   - Among many observations, Northern community members identified strengthening local diagnostic laboratory capacity as a priority, and a strong incentive to participate in health research.
   - This strongly influenced the final design of the project (see below).
2. Nunavik study site preparation:

   2.1. Establishing new study site:
   - » The original project was planned for Puvirnituq, but in April 2015 challenges arose that made this impossible:
     - * The Director of the Sarliatauvik Child Care Center stepped down, and was not replaced for several months.
     - * The coordinator of the microbiology laboratory in Puvirnituq also stepped down at that time and was not replaced for several months.
   - » We had a successful exploratory mission to Kuujjuaq in August 2015 to engage community members.
   - » Kuujjuaq is the largest town and the administrative capital of Nunavik. In 2011, the total population was 2,375 people, including 235 children aged 0-4 years. The Iqitauvik and Tumiapiit Child Care Centers are the only daycare centres in the town and are attended by 160 children on two sites. Provincial subsidies for childcare care in Québec enable the majority of preschool-age children in the town to attend daycare (i.e. 160 (68%) of 235 children). Children attending daycare will constitute the study population in Kuujjuaq.
   - » Presentations were given to the Board of Governors of both daycares in town, medical corps, microbiology laboratory, and to the Kativik Regional Government (KRG) for permission to proceed.

   2.2. Implementing near-care molecular diagnostics for routine use in Kuujjuaq:
   - » PI (Yansouni) was appointed "Designated Microbiologist Consultant for Nunavik".
   - » We advised laboratory coordinators on priority technologies to implement for improving care in remote northern communities. This led to the implementation in December 2015 of the BD Max PCR platform for rapid molecular detection of several pathogens.
   - » Although this platform is implemented for clinical use, implementation in Kuujjuaq will allow for study microbiology to be performed locally by hospital staff, and results can be used clinically to guide the management of people found to harbour infections during the study. This is a major asset to the community as well as to the study.

» We reached an agreement with the Kuujjuaq microbiology lab coordinator on use of the BD Max during the study.

3. Nunavut study site preparation – Iqaluit:

- Co-PI (Goldfarb) is working with partners in Iqaluit to arrange study logistics.
- We are communicating with the Medical Advisory Committee (MAC) of the Qikiqtani General Hospital about the BioFire® FilmArray instrument for near-care rapid molecular diagnostics of enteric infections.

4. Establishing outside funding streams:

- ArcticNet funding was used to leverage no-cost extensions for RI-MUHC startup funds.
- ArcticNet funding was used to leverage two investigator-initiated research grants:
  » BD Biosciences (Canada) "BD Collaboration: Diarrheal Illness and Enteric Infections among Young Children in Nunavik and Nunavut" [**Total value CAD$ 70,000 in-kind reagents**].
  » BioMérieux "Using state-of-the-art diagnostic strategies to prevent morbidity from enteric infections in remote areas where conventional diagnostics fail" [Cash CAD$ 57,450, equipment CAD$ 50,000, Reagents CAD$ 100,800: **Total value CAD$ 208,250**].

5. Determining molecular methods to be used in study:

- Our original plan was to perform all microbiological testing as large batches every four months at McMaster and McGill.
- The nearly CAD$ 400,000 difference between funding requested and funding awarded required us to reconsider our planned methods.
- Moreover, results of our CIHR-funded planning meeting "Building an Arctic Enteric Infections Research Agenda" in Iqaluit 22-23 March 2015 clearly indicated that infrequent batch testing in the South would not engage communities to participate in the research.
- We used two mitigation strategies: (1) We sought synergies with the local health system in Kuujjuaq to adapt our protocol to the molecular diagnostic platform best suited to their current needs, and actively assisted in the implementation of the BD Max platform there. (2) We engaged diagnostics industry partners with investigator-initiated research proposals.
- In Kuujjuaq, BD Bioscience (Canada) will provide CAD$ 70,000 in reagents for the BD Max.
- In Iqaluit, where no local molecular testing for enteric infections is currently available, BioMérieux will provide a BioFire® FilmArray instrument as well as CAD$ 100,800 in reagents. This Health-Canada approved platform will allow results to guide clinical management and could easily be implemented in the routine clinical lab in Iqaluit.
- In both research locations, same-day clinical results will now be available.

6. Coordinating activities with other network teams:

- As advised by ArcticNet, we met with the Sherilee Harper team to coordinate our activities in Nunavut: Iqaluit in-person meeting March 2015, Montreal in-person meeting July 2015, Vancouver in-person meeting Dec 2015.
- There were regular conference calls between teams with the aims of harmonizing CRFs, microbiological methods, and study protocols.
- Harper, Goldfarb, and Yansouni co-organised the ASM 2015 Topical session: **The Scoop on Northern Poop**; accessible at http://www.arcticnetmeetings.ca/asm2015/docs/topical-session-agenda.pdf
- We coordinated planned activities with the team performing the Nunavik Health Survey

2017 (Team Leader: Pierre Ayotte) regarding investigations of enteric infections.

7. Research protocol and ERB submission:

   - All key elements are now in place to develop a final research protocol, with planned submission to ERBs by March 2016.

There are no Results or Discussion sections in this project.

CONCLUSION

This project now has the financial and logistical requirements to meet the objectives described in the proposal we submitted. Moreover, we have successfully leveraged ArcticNet NCE funds to obtain significant funding from industry partners. In so doing, we have enhanced the relevance and acceptability of these projects to the communities involved by implementing diagnostic services yielding results in a clinically meaningful timeframe during the study.

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SECTION IV. NORTHERN POLICY AND DEVELOPMENT

Section IV is composed of three ArcticNet research projects discussing national and international policies in relation to the Canadian Arctic socio-economic development in a context of rapid environmental change and modernization.

A "Regional Seas Arrangement" for the Arctic Ocean

Project Leader

Michael Byers (University of British Columbia)

Network Investigators

Suzanne Lalonde (Université de Montréal)
David VanderZwaag (Dalhousie University)

Collaborators

Betsy Baker (University of Alaska Fairbanks)
Paul Crowley (World Wildlife Fund Canada)
Robert Hage (Department of Foreign Affairs and International Trade (retired))
Bjorn Kunoy (Ministry of Foreign Affairs, Faroe Islands)
Ted McDorman (University of Victoria)
John Merritt (Nunavut Tunngavik Incorporated)
Erik Molenaar (University of Tromso)
Alexander Vylegzhanin (Russian Academy of Sciences)
Brooks Yeager (Birdwell Strategies)
Willy Østreng (Norwegian Scientific Academy for Polar Research)

HQP

Hema Nadarajah, Doctoral Student (University of British Columbia)
Malgorzata Smieszek, Doctoral Student (Arctic Centre, University of Lapland)
Kelsey Franks, Honours Undergraduate Student (University of British Columbia)

Northern HQP

Bruce Uviluq, Northern Student (Nunavut Tunngavik Incorporated)

ABSTRACT

The Arctic Ocean is almost entirely surrounded by the landmasses of its five coastal states (Canada, Greenland-Denmark, Norway, Russia, and the United States). It is largely a circulating system in which currents, ice, fish, and marine mammals constantly move across national boundaries. Effective management of this system increasingly depends on cooperation among Arctic Ocean coastal states, indigenous peoples, some non-Arctic states and intergovernmental organizations like the EU, and non-state actors such as environmental groups and shipping companies. The UN Convention on the Law of the Sea requires states to cooperate "in formulating and elaborating international rules, standards and recommended practices and procedures … for the protection and preservation of the marine environment, taking into account characteristic regional features." In support of this obligation, the UN Environmental Program (UNEP) has promoted the creation of "regional seas arrangements" (RSAs) to enhance the environmental management of ocean spaces. Today, more than 143 states participate in 14 RSAs established under the auspices of UNEP, and another four RSAs that were established independently. The best-known RSA is the 1992 OSPAR Convention ("Convention for the Protection of the Marine Environment of the North-East Atlantic"), which establishes the OSPAR Commission and brings together 15 states, the European Union, and observers from 27 non-state actors. In September 2014, the US Special Representative for the Arctic, Admiral Robert Papp, announced that the United States was considering promoting an RSA for the Arctic Ocean during its 2015-2017 chairmanship of the Arctic Council. This project explores the potential for an Arctic Ocean RSA. It examines how an agreement could best be designed to: (1) promote and complement the roles of the Arctic Ocean coastal states; (2) promote and complement the role of the Arctic Council; (3) centrally include Arctic indigenous peoples; and (4) take into account the views and interests of other non-state actors. Finally, this project will produce and disseminate a model Arctic Ocean RSA.

KEY MESSAGES

- The Arctic Ocean is largely a circulating system in which currents, ice, fish, and marine mammals constantly move across national boundaries.
- The Arctic Ocean faces numerous management challenges, including jurisdictional uncertainties (extended continental shelves, the Beaufort Sea boundary dispute, the Northwest Passage and Northern Sea Route), shipping, security and rescue, emergency response, seabed activities, fisheries and other living resources, biodiversity, land-based pollution, climate change and black carbon.
- The UN 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 possible steps that could be taken under the umbrella of "ecosystem based management", including marine protected areas and regional seas arrangements (RSAs). This project examines these options and the role that the Arctic Ocean coastal states, Arctic Council, indigenous peoples, scientists, shipping companies and other non-state actors could play.

OBJECTIVES

- Development, refinement and publication of a model Arctic Ocean RSA.
- Publication, by a leading university press, of the model Arctic Ocean RSA and fifteen supporting papers on different issues of Arctic Ocean governance.

INTRODUCTION

The Arctic Ocean is almost entirely surrounded by the landmasses of its five coastal states (Canada, Greenland-Denmark, Norway, Russia, and the United States). It is largely a circulating system in which currents, ice, fish, and marine mammals constantly move across national boundaries. Effective management of this system increasingly depends on cooperation among Arctic Ocean coastal states, indigenous peoples, some non-Arctic states and inter-governmental 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 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.

This project explores the options for increased international maritime cooperation in the Arctic Ocean, including an Arctic RSA.

At a planning workshop involving the three network investigators and two key collaborators in September 2015, it was decided that a firmer research foundation was needed before drafting of a model Arctic RSA could begin. For this reason, we decided to commission papers on fifteen specific topics of Arctic Ocean governance:

- Extended continental shelves;
- Maritime boundaries and joint management regimes;
- International straits and internal waters;
- Shipping;
- Search and Rescue & Emergency Response;
- Security;
- Seabed Activities;
- Living Marine Resources;
- Biodiversity;
- Land-based Pollution;
- Climate Change and Black Carbon;
- Ecosystem Based Management;
- Arctic Council;
- Indigenous Peoples Cooperation;
- Scientific Cooperation

At the end of the project, we will submit these papers along with the model Arctic RSA to a leading university press—in order to maximize the accessibility, influence and "shelf-life" of our research.

ACTIVITIES

The project is proceeding through a number of distinct stages. Up to this point, we have accomplished the following:

1. Literature review – The literature on Regional Seas Arrangements (RSAs) and Ecosystem-based Management (EBM) has been collected, examined, and synthesized.
2. Planning workshop – The three Network Investigators met for a planning workshop in Ottawa on September 21, 2015. Two key collaborators (Betsy Baker from the University

of Washington and Paul Crowley from WWF Canada) also attended, along with two doctoral students (Hema Nadarajah from UBC and Malgorzata Smieszek from the University of Lapland).

3. Consultations – Informal consultations with decision-makers and stakeholders have begun. For instance, Michael Byers met with David Balton (US Chair of the Arctic Council) at the GLACIER conference in Anchorage in August 2015, with Sheila Watt-Cloutier (former chair of the Inuit Circumpolar Council) in Vancouver in September 2015, and with a number of other Arctic indigenous leaders at a conference organized by Arthur Yuan and Terry Fenge in Ottawa in December 2015.
4. Publishing – The Network Investigators and Collaborators are already publishing as a result of their work in the project. For example, in September 2015, Betsy Baker and Brooks Yeager published an article entitled "Coordinated Ocean Stewardship in the Arctic: Needs, Challenges and Possible Models for an Arctic Ocean Coordinating Agreement," in the journal Transnational Environmental Law. Michael Byers has a chapter on "The Law and Politics of the Lomonosov Ridge" appearing soon in Myron Nordquist, *Challenges of the Arctic: Continental Shelf, Navigation, and Fisheries* (Dordrecht: Brill, 2016). David Vanderzwaag has two chapters that have just been published in peer-reviewed books, one on "Controlling the Long-range Transport of Persistent Organic Pollutants (POPs) into the Arctic", the other on "Climate Change and the Shifting International Law and Policy Seascape for Arctic Shipping."
5. Conference attendance – The Network Investigators and Collaborators have already spoken at numerous conferences on topics addressed by the project. For example, David VanderZwaag spoke on "The International Seascape for Shipping: Conflict, Cooperation, Challenges" at the Warming Arctic International Inquiry Conference at Tufts University in April 2015, while Michael Byers spoke about the role of scientific cooperation in Arctic Ocean politics on the opening plenary panel of the ArcticNet ASM in December 2015.

We are now moving into the following stages of the project:

1. Project team workshop – The project team will hold a workshop in June 2016 to discuss the 15 draft papers and how, specifically, they inform a draft model Arctic Ocean RSA.
2. Book proposal – Following the project team workshop, a book proposal will be developed and submitted to a leading university press. At the same time, the draft papers will be revised, augmented and refined in light of input from the workshop and the Network Investigators.
3. Drafting of model Arctic Ocean RSA – The draft papers and workshop discussion will be used as a basis for the first draft of a model Arctic Ocean RSA. This draft will be circulated for comment to the entire project team, as well as to Northern governments, Arctic indigenous peoples, Arctic Council committees and task forces, environmental groups, companies and industry associations.
4. Completion of papers and model Arctic Ocean RSA – As the draft papers are being revised, they will receive substantial editorial input from the Network Investigators. And based on input received from the papers, the Network Investigators will concurrently produce a first draft of a model Arctic RSA, which will be circulated back to the authors for comment.
5. International conference – The papers and model Arctic Ocean RSA will provide a focus for an international conference that brings the project team together with different stakeholders (Arctic governments, Arctic indigenous peoples, environmental groups, companies and industry

associations) as well as other international experts and the media.

6. In parallel with the international conference, the model Arctic Ocean RSA will be widely disseminated, including through the book—which we hope to publish in late 2018.

RESULTS

Although this project is still in its early stages, we have developed a comprehensive view of the existing literature, published a number of initial papers, and adjusted our overall plan to take into account current developments. We are now in the process of commissioning fifteen specific papers to support the drafting and publication of a fully informed, well-crafted model Arctic regional seas arrangement.

DISCUSSION

In August 2015, it became clear that the United States had pulled back from its plan to negotiate a full Arctic Ocean Regional Seas Arrangement during its 2015-2017 chairmanship of the Arctic Council. The US is instead planning to advance a looser set of initiatives under the umbrella of "ecosystem based management". According to David Balton, 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.

At our September 2015 planning workshop, the three Network Investigators decided that our project needed to take a more comprehensive approach than initially planned, in order to develop a knowledge base that is broad and deep enough for us to draft a model Arctic Ocean RSA in the absence of a parallel, official, US-led process. For this reason, we are commissioning papers on fifteen specific topics of Arctic Ocean governance. These papers will be work-shopped in June 2016. We will then seek to develop and refine those papers for publication and also, concurrently, begin the process of drafting and consulting on a model Arctic Ocean RSA.

CONCLUSION

The project is making excellent progress after a necessary adjustment, one that results from a change in the US approach to the issue of Arctic Ocean governance during its 2015-2017 chairmanship of the Arctic Council. We have conducted an extensive literature review, identified fifteen key issues, and are presently commissioning papers for a workshop in June 2016. On the basis of those papers, which we plan to publish with a leading university press, we will press ahead with the drafting of a model Arctic Ocean regional seas arrangement (RSA), in the hope that this will embolden the United States and other Arctic countries to follow.

ACKNOWLEDGEMENTS

The Network Investigators are deeply saddened by Terry Fenge's death in November 2015. Terry's expansive knowledge of Arctic issues and his connections with Arctic indigenous peoples made him an almost essential Collaborator in this project. We move forward in his memory.

We also wish to acknowledge the key role that Paul Crowley of WWF Canada played in our September 2015 planning meeting. Paul, with his connections to the environmental movement and Arctic indigenous peoples, brings invaluable experience and insight to our project.

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Supporting Understanding, Policy and Action for Food Security in Nunavik and Nunatsiavut

Project Leader

Chris Furgal (Trent University)

Network Investigators

Christopher Fletcher (Université Laval)
Cedric Juillet (Trent University)
Mélanie Lemire (Université Laval)
Michel Lucas (Centre de Recherche du Centre hospitalier de l'Université Laval)

Collaborators

Amélie Bouchard (Nunavik Regional Board of Health and Social Services)
Francoise Bouchard (Nunavik Regional Board of Health and Social Services)
Serge Déry (Nunavik Regional Board of Health and Social Services)
Kristie Jameson (Food Security Network of Newfoundland and Labrador)
Elena Labranche (Nunavik Regional Board of Health and Social Services)
Lea Laflamme (Nunavik Regional Board of Health and Social Services)
Catherine Pirkle (Centre de Recherche du Centre hospitalier de l'Université Laval)
Vinay Rajdev (Trent University)
Tom Sheldon (Nunatsiavut Department of Lands and Natural Resources)
Lisa Teh (University of Hawaii)
Michele Wood (Nunatsiavut Government)

HQP

Lara Gautier, Doctoral Student (Université de Montréal)
Kristeen McTavish, Masters Student (Nasivvik Centre for Inuit Health and Changing Environments)
Lindsay Thackeray, Masters Student (Trent University)
Emily Willson, Masters Student (Trent University)
Community freezers in Nunatsiavut: benefits and risks for sustainable food security in Inuit communities
Myriam Fillion, Post-Doctoral Fellow (University of Ottawa)

Northern HQP

Clara Noah, Northern Research Staff (Niqitsiavut Society)

ABSTRACT

Food insecurity is a critical public health issue in many northern communities today. Various forms of environmental, socio-cultural, economic and political change threaten northern households' abilities to access and acquire adequate, healthy, safe and preferred foods on a regular basis. Action is needed to address this issue but must be based on accurate and relevant information gathered at the appropriate scale. This project is being conducted in cooperation with the Nunavik Regional Board of Health and Social Services and the Nunatsiavut Government to support Nunavik and Nunatsiavut residents, and community and regional organizations in understanding and taking action on food insecurity at the community and regional scales. The project involves household food security surveys in Nunavik, analysis of existing datasets in the two regions to determine the role of various factors, including existing food support programs, in household food security status, and a policy and program review and knowledge translation activities to support decision making and policy discussions in the two regions to address long term food security challenges.

KEY MESSAGES

- There is a significant and growing body of literature on food security in the circumpolar North that is predominantly focused in the Canadian Arctic; several key gaps still exist in this literature and are critical to fill to enhance our understanding of this issue (e.g. food availability, political protection to access, food utilization).
- While no currently existing food security assessment tool adequately evaluates all domains of the concept in Inuit communities, the Household Food Insecurity Access Scale appears to address the largest number of priorities applicable to the Inuit food context.
- While it performs relatively well, the Household Food Insecurity Access Scale does not do as good a job at identifying individuals who are relatively food secure or very food insecure (e.g. hungry).
- There is significant variation in the prevalence of household food security across communities participating in this study; this is potentially indicative of significantly different food realities being experienced between communities even in the same region and argues for the need for community scale data to better understand this issue in the Arctic.
- As hypothesized, but not yet shown in existing datasets, the level of participation in hunting and fishing activity appears to have a significant effect on Inuit household food security status.
- Evaluation of food security interventions must include implementation evaluation to determine the extent to which an intervention functioned, and why.
- Evaluation of the impact of food security interventions can be aided by the use of the alternate Health Eating Index (a-HEI) to assess the association between nutritional profile and food security status; analysis of data for an intervention with pregnant women in Nunavik shows that women that were more food insecure scored lower on the health eating index scale.

OBJECTIVES

1. Increase understanding at the household and community scales of status and determinants of food insecurity in the two regions and the role of specific food support programs;
2. Adapt and validate a food security assessment tool for use in Inuit communities and apply it in a pilot trial in Nunatsiavut and through the Qanuippitaa survey in Nunavik;
3. Conduct policy and program review and knowledge translation activities to support

decision making and policy discussions in the two regions to address long term food security challenges.

INTRODUCTION

The Canadian Council of Academies expert panel assessment on Aboriginal food security in northern Canada concluded “that there is a food crisis in northern Canada. This crisis, which is more evident in Aboriginal populations, has long-term implications for the health and well-being of these communities” (CCA, 2014: 193). Various forms of environmental, socio-cultural, economic and political change all threaten northern households’ abilities to access and acquire adequate, healthy, safe and preferred foods on a regular basis. Sixty-two percent of Inuit households in Canada are considered to be food insecure (Huet et al., 2012). At the regional level, these rates range from 24% in Nunavik (note: not a comparable statistic to the USDA HFSSM generated level reported for other Inuit regions) to nearly 70% in Nunavut (Rosol et al., 2012). Inuit communities face increasing challenges of accessing adequate nutrition including high costs and limited availability of healthy foods, increasing cost of hunting and harvesting traditional food, limited employment opportunities and low household incomes, changing dietary habits, limited awareness of healthy eating habits, and various forms of environmental change (climate change and variability, presence of environmental contaminants etc.) (Lambden et al., 2006; CCA, 2014; Organ et al., 2014). These challenges have been associated with a nutrition transition in many Inuit communities where growing consumption of low-nutrient- store-bought foods and decreasing consumption of traditional foods are contributing to the increasing prevalence of diet-related health problems, such as obesity, diabetes, and cardiovascular disease amongst populations that have traditionally experienced low levels of such conditions (Mead et al., 2010, Egeland et al., 2010). Individuals who are food insecure have significantly higher odds of being overweight, having poorer nutritional status, are at greater risk for many chronic diseases, have poorer functional health and experience slower growth (Willows et al., 2011, Pirkle et al., 2014). The CCA expert panel was warranted in calling this a crisis situation, and one needing immediate action. However, action must be based on robust information focused at the appropriate scale, considerate of the most relevant factors and aware of the fact that it often requires the coordinated engagement of a diversity of partners to have sustained impact on this topic (Wakegejig et al., 2013).

Despite recognition of the importance of the issue of food insecurity in Inuit communities there are still significant challenges to providing decision makers at the household, community or regional level with the needed information upon which to take informed action. Issues of reliability, validity and spatial and temporal comparability of food security rates exist because of a lack of previous validation of the widely, but inconsistently used USDA Household Food Security Survey Module in many Inuit communities (CCA, 2014). A lack of examination of scale in previous and current data collection efforts has minimized our understanding of the importance of such things as sharing networks in food security status in Inuit communities. Finally, despite the growing number of interventions / programs developed and implemented to address this issue few initiatives have been evaluated in regards to their impacts on household food security status, and individual food behaviours (CCA, 2014).

In cooperation with the Nunavik Regional Board of Health and Social Services and the Nunatsiavut Government, this project is working to support Nunavik and Nunatsiavut residents, and community and regional organizations to understand and take action on food insecurity at the community and regional scales.

ACTIVITIES

We have been conducting activities in 2015-16 to meet the identified objectives of the research project through a number of collaborative research endeavours. For each of the 11 research activities the activity leaders, project objectives being met, and key results are presented (when possible for work that has produced results that can be presented at this time). Following the presentation of activities and key results, a general discussion of findings and conclusions is presented.

Activity 1: Review and Analysis of Circumpolar Food Security Literature

Activity leads: Furgal, Rajdev

Objectives: 1, 2, 3

While food security in the circumpolar region has been identified as a critical issue affecting many Arctic communities very little is known of what exists in the literature discussing the issue of food security; hence, the objective of this project was to identify the trends in the study of food security in peer-reviewed and grey literature in the circumpolar region by conducting a systematic literature review. The peer-reviewed literature was searched using three electronic library databases. The grey literature was searched using three online search engines and three agency websites. A total of 740 publications were collected that discussed food security and/or components of food security (i.e. food availability, food accessibility and food quality) ranging between the years 1953 and 2015. Additionally, all available food security survey or assessment tools were gathered and identified (see Activity «*Review and evaluation of existing food security tools and their applicability for the Inuit food context* »)**.**

Results

Both the peer reviewed and grey literature show an exponential growth in food security-focused study in the circumpolar region. A larger proportion of the publications relate to the Inuit population (72%). The majority of the circumpolar literature on the topic is focused on Arctic Canada, followed by Alaska and then Greenland. The majority of sources speak to the issue of food quality (90%), followed by food accessibility (40%) and finally food availability (17%). There has been an increase in publications about food security in the circumpolar region over time. The trends reflect a research focus on the topic and increased interest in the nutrient and chemical, and cultural qualities of food, and social and economic accessibility of food. Greater attention needs to focus on food availability, political and physical accessibility of food and biological quality of food. They are currently poorly understood issues in the field of food security and underrepresented in the current literature. The results of this systeamtic literature review were presented at the 2015 ArcticNet ASM and are the focus of a publication currently under development.

Activity 2: Nunavik regional ranking and prioritization for food security tool adaptation

Activity leads: Furgal, Lucas, Pirkle

Objectives: 2, 3

One of the goals of this project is to work with regional decision makers to identify limitations in current food security assessment data and tools, and identify priorities for tool adaptation or development. To this end, this past year we conducted a consultation process and ranking exercise with members of the Nunavik Nutrition and Health Committee (NNHC) in regards to their needs and desires with future food security assessment tool development and adaptation. A presentation of the work of this project was provided at the fall NNHC meeting and a list of previously identified potential priorities for future Inuit food security assessment tools was presented. Membership of the committee was asked to rank priorities in order of importance.

Results

Table 1 provides a final ranking of priorities based on participants score. The result highlight the desire of regional decision making authorities to have a food security assessment tool that first provides information or results on which clear action can be taken to address food insecurity in the population. Second overall, was the priority to have a food security assessment tool that was inclusive of all of the domains of the concept. The issues of spatial scale, seasonality followed closely in the ranking and then a number of priorities were grouped together in the ranking among members.

Activity 3: Review and evaluation of existing food security tools and their applicability for the Inuit food context

Activity leads: Furgal, Willson

Objectives: 1, 2, 3

This activity sought to review a series of food security tools and models to summarise and assess their ability to address the different domains included within the concept of food security (availability, accessibility, quality, utilization), as well priority criteria that were identified by the Nunavik Nutrition and Health Committee. First, a systematic review of a series of food security tools and models was conducted to identify and summarize key information, or key

Table 1. Ranking of priorities for future food security assessment tools to be used in Nunavik, according to members of the Nunavik Ntrution and Health Committee.

Description of what the tool should do	Summary of NNHC ranking of priority
Include questions on each of the elements of food security (food availability, accessibility, quality (safety, nutrition) and utilization (knowledge, skills, preferences)	2
Be comparable with the Qanuippitaa 2004 dataset	5
Be comparable with other Inuit regions in Canada	5
Be comparable with other regions globally	8
Consider the spatial scale at which food security is understood in Nunavik (household, Vs community, Vs regional)	3
Provide evidence on dimensions of food security for which action can be taken at a regional or community scale	1
Consider seasonality / temporal scale at which food security is important	4
Consider stability of food security status over time	5

features (e.g. number of domains of food security considered, mode of food access, spatial scale, etc), of each tool and model. The list of food security tools and models were also thematically categorized, based on their overarching objectives (e.g. a tool for assessing food security, a tool to assess food availability, etc). The features that emerged from the initial systematic review were then included into a list of priority criteria, which also included a list of criteria identified by a food security working group (e.g. comparable with other Inuit regions, comparable to other regions, questions on evaluation of food security programs, etc). This resulted in a list of 14 different criteria that each tool and model was then assessed on. This was done through a cross-case comparison that quantified the presence or absence of each of the 14 criteria within each tool and model. Specifically, each criterion used a scoring system (e.g 0=absent, 1=present-poor, 2=present- strong) and each tool and model received a score. Total scores were then calculated for each tool and model, by summing the scores of the 14 criteria (Table 2). The highest score a tool could receive was 29, indicating that a tool or model effectively addressed all 14 of the identified criteria.

Results

In total, 27 tools and models were reviewed and scored. Each tool and model fell into one of five themes, including: tools for assessing food security, tools for assessing outcomes of food security, tools for assessing food accessibility, tools for assessing food availability, models for assessing and identifying impacts on food security. Based on the scoring system for each of the criteria, the highest score that a tool could receive was 29. The tool that received the highest score was the Household Food Insecurity Access Scale (score, 14). Other highly ranked tools included the USDA Household Food Security Survey Module (HHFSSM) (13), the Household Hunger Scale (13), Standard 6-item subset of the HHFSM/ Aboriginal Peoples Survey (12), Food Insecurity Experience Scale (12), and the Months Inadequate Household Food Provisioning tool (11). In order to

Table 2. Summary list of food security tools and models and associated evalaution scores.

TOOLS FOR ASSESSING FOOD SECURITY STATUS	
Tool	***Score***
USDA Household Food Security Survey Module (HHFSSM)	**13**
Standard 6-item subset of the core module (HHFSSM)	**12**
Household Food Insecurity Access Scale	**14**
Qanuippitaa (Nunavik Inuit Health Survey)	**10**
Aboriginal Peoples Survey	**12**
Food Sufficiency Question	**9**
The Expanded Food and Nutrition Education Program (EFNEP) Evaluating/Reporting System question	**6**
Behavioural Risk Factor Surveillance System Questions	**8**
Radimer/Cornell measures of hunger and food insecurity.	**8**
Food Insecurity Experience Scale	**12**
TOOLS FOR ASSESSING OUTCOMES OF FOOD SECURITY	
Tool	***Score***
Household Hunger Scale (HHS)	**13**
Prevalence of Undernourishment	**8**
Global Hunger Index (GHI)	**3**
Community Childhood Hunger Identification Project (CCHIP) hunger index.	**9**
Anthropometry	**6**
Coping Strategies Index (CSI)	**7**
TOOLS FOR ASSESSING FOOD ACCESSIBILITY	
Tool	***Score***
Share of Food Expenditure	**6**
Domestic Food Price volatility	**7**
Household Consumption and Expenditures Survey (HCES)	**7**
TOOLS FOR ASSESSING FOOD AVAILABILITY	
Tool	***Score***
Months Inadequate household food provisioning	**11**
Household Dietary Diversity Score (HDDS)	**7**
Food Consumption Score (FCS)	**8**
Relative dietary supply index	**7**
MODELS FOR IDENTIFYING IMPACTS ON, AND ASSESSING, FOOD SECURITY	
Tool	***Score***
The Household Economy Approach (HEA)	**5**
Comprehensive Food Security and Vulnerability Analysis (CFSVAs)	**5**
Famine Early Warning Systems Network (FEWS NET)	**5**
Global Food Security Index (GFSI)	**10**

effectively address all domains or aspects included in the concept of food security, and identified priority criteria, results indicate the need for the development of more comprehensive measures of food security, or modification of current tools. Modifications could include, integrating tools, or adding particular questions from existing tools (e.g. USDA, HFIAS, Months Inadequate Food Provisioning) to others. The results of this review and evaluation will be presented to the Nunavik Food Security and Nutrition Working Group this spring.

Activity 4: Psychometric validation of the Household Food Insecurity Access Scale among Inuit women from Northern Quebec

Activity leads: Pirkle, Teh, Lucas, Furgal

Objectives: 2, 3

During pregnancy, food security, which includes access to enough safe, nutritious, and culturally appropriate food, is a major concern for the people of Nunavik and many other communities globally. Food insecurity, which is when people and communities do not have enough safe and nutritious food, can negatively impact the health of mothers and developing fetuses. In order to understand the status of this issue with all pregnant women in Nunavik, we need to develop an easy, fast, and culturally appropriate way of measuring food security specific to this community. Questionnaires are the fastest, cheapest, and least-invasive way to measure food security; however, not all questionnaires work well for all people. For example, most of the questionnaires developed for other communities put too much emphasis on market foods. In Nunavik, it is important that questionnaires include questions about country foods as well.

As part of the Arctic Char Distribution Program designed to help address contaminant exposure and food insecurity among pregnant women in Nunavik, a modified HFIAS was administered to 131 pregnant women and blood samples were taken to measure nutritional biomarker concentration. This year we partnered with the researchers involved in that intervention and conducted analysis of the food security tool used and its performance in reporting food insecurity among the participants was explored in support of Objectives 2 and 3 of this study. Data were fit to a Rasch Rating Scale Model (RSM) to determine HFIAS discrimination ability. Several other models were constructed and tested against the original model using Akaiki Information Criterion (AIC) and Bayesian Information Criterion (BIC), which indicate relative information loss with each model. An exploratory factor analysis (EFA) was conducted on the items that the RSM indicated provided the most information. Receiver Operating Characteristic (ROC) curves were used to assess the level of food insecurity associated with clinically low levels of iron depletion biomarkers.

Results

The RSM indicated that the scale as a whole showed a good discrimination ability (infit mean square; MSQ=0.727 to 1.283 per item; Figure 1). However, some potential problems with some of the items were detected. Subsequent analyses indicated that dropping two items that might not be culturally relevant produced a preferred model (AIC=1153.086, BIC=1178.894 vs. AIC=1523.718, BIC=1555.261 for the original model; Figure 2). Infit statistics (MSQ=0.783 to 1.313) for the modified model were also within the productive range for each item. Adding an item asking about country food consumption provided information about food security (Figure 3), although it somewhat reduced the overall model fit. ROC curve analysis is currently in progress.

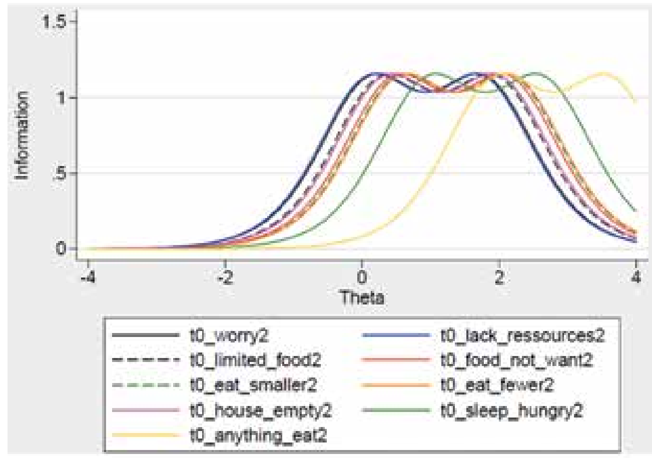

Figure 1. Item Information Function following Rasch RSM on the original HFIAS in Nunavik. Note: Theta=0 likely indicates average food insecurity in this sample. Higher theta levels suggest higher food insecurity. Higher levels of information indicate better discrimination ability of each item.

Statistical analyses on the HFIAS data shows that the survey, versus characteristics of the specific sample, accounted for an acceptable amount of the total score. These analyses can help us to make sure we are only using the best questions to test the survey's ability to measure the nutritional consequences of food security/insecurity. One concern is that the HFIAS does not do as good a job as we would like at identifying individuals who are relatively food secure or very food insecure (e.g. hungry). This problem is addressed fairly well by replacing some questions on the questionnaire that are not as good with some of the country food questions. Work on the analyses with the levels of

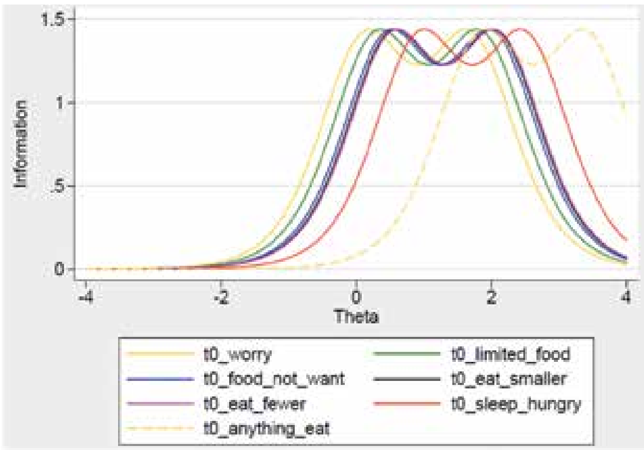

Figure 2. Item Information Function following the Rasch RSM on the modified version of the HFIAS in Nunavik without the country food item. Note: Theta=0 likely indicates average food insecurity in this sample. Higher theta levels suggest higher food insecurity. Higher levels of information indicate better discrimination ability of each item.

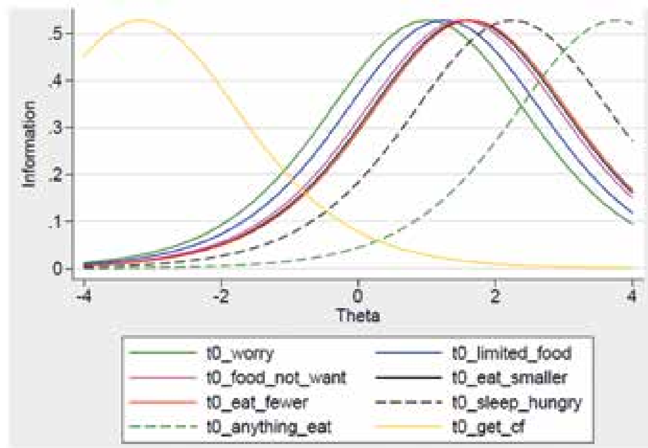

Figure 3. Item Information Function following the Rasch RSM on the modified version of the HFIAS in Nunavik with the country food item. Note: Theta=0 likely indicates average food insecurity in this sample. Higher theta levels suggest higher food insecurity. Higher levels of information indicate better discrimination ability of each item.

nutrients in pregnant women's blood continues and analysis will be completed this spring/summer. Initial communication of these findings is underway with the NRBHSS and NNHC.

Activity 5: Qualitative conceptualization and adaptation of Inuit food security assessment tool

Activity leads: Furgal, Willson

Objective: 2

As part of this project and the Community-led Food Assessment project funded through the Public Health Agency of Canada and being led by the Food Security Network of Newfoundland and Labrador (now Food First NL), we have been developing a process to gather qualitative information in Nunatsiavut to explore the notion of food security or insecurity from a regional perspective. Many of the tools that are currently in use in the Canadian North to assess household food security are critiqued for not being culturally appropriate, or not using terminology or words applicable to local contexts in these regions. In addition to work on evaluation and validation of currently used tools and their abilities to identify household food insecurity and its associations with critical health outcomes (see reporting on other Activities in this report), we are conducting focus groups with a stratified cross section of community populations in three Nunatsiavut communities this spring. This qualitative data will be used to identify missing elements of the notion of food insecurity in this, and perhaps other, regions that may not be included in current assessment tools. As well, these focus groups will help us determine the appropriate words, phrases, or terminology to use in food security assessment tools and further adapt existing tools for future use. This activity will aid significantly in our adaptation of the tool to be used in the next round of food security surveys in Nunatsiavut (in 2016-17 under this project) and Nunavik (in 2017-18 under this project and in cooperation with the Qanuilirpitaa regional health survey in Nunavik).

Activity 6: Ongoing Analysis of Community level food security status data in Nunatsiavut and Baker Lake, Nunavut

Activity leads: Furgal, McTavish, Willson

Objectives: 1, 3

Analysis of the household food security status data gathered in Nunatsiavut is ongoing and we anticipate returning results to communities this spring. A representative sample of households were sampled using the USDA HFSSM (USDA Household Food Security Survey Module) in all coastal Nunatsiavut communities in addition to exploring self-reported food needs and the current use of various existing food support programs. We have remained in close communication with the regional representatives and community committees for this work and are planning return of results later this spring. Results will be reported here (ArcticNet reporting) once released in the communities and regions to respect the agreement and relationship we have with the community and regional partners. To date it can be noted though that the significant variability in results we have obtained for each of the participating communities is indicative of food security conditions and realities being substantially different at the community scale.

In October 2015, in association with the Public Health Agency of Canada funded project in partnership with the Food Security of Newfoundland and Labrador (now called 'Food First NL') we conducted a community wide household assessment of food security and food needs levels in the community of Baker Lake, NU. This work was conducted in association with the Niqitsiavut Society (local community food security committee) in support of their community led food assessment. While not originally planned under this program, it has provided us with an additional study site to look at food security status in an Inuit community, the performance of the existing food security assessment tools, conduct program review (association between household food security status and use of various community food support programs) and provide information back to another community interested in taking action on its food system to address challenges with food insecurity. Surveys were conducted with a representative sample of households in the community via iPad interviews and preliminary results were discussed with the community committee prior to departing the community. Analysis of the data is ongoing and it is anticipated that results will be returned and discussed with the Niqitsiavut Society committee late this spring. We anticipate seeking out additional funding in the future to replicate this survey in the community to look at piloting the adapted food security tool we are developing under this project and examining changes in food security status over time.

Activity 7: Examination of determinants of food security status in Nunavik through Bayesian modeling

Activity leads: Juillet, Furgal

Objectives: 1, 2, 3

In Nunavik, a previous analysis we conducted on the "*Qanuippitaa? How Are We?* 2004" public health survey dataset reported community food insecurity levels ranged from 9% to 51%, while the overall regional rate was 24% (as measured by one question asking about a lack of food in the month prior to the survey). Despite these results, little was revealed about the determinants of food insecurity in the region and their relative importance. Based upon data from the same household questionnaire, in conjunction with the individual questionnaire of the *Qanuippitaa? How Are We?* 2004 survey, the present study investigated the relative importance of determinants of reported household lack of food in Nunavik using generalized linear mixed models and model selection, based upon information criteria, while accounting for redundancy in explanatory variables.

Results

Our analyses provide strong evidence for a negative relationship between a reported household lack of food in the month prior to the survey and a synthetic index positively associated with seasonal harvesting frequencies reported by the household respondent (444 answers; Figure 4).

After controlling for different sources of methodological biases (e.g. interviewer effect), our analyses did not indicate strong support for other social, economical, demographic and geographic determinants of food insecurity that were hypothesized to explain the pattern of answers within Nunavik communities and households. These results indicate that while often focussing on differences in food insecurity rates between regions, sub-regions or communities, one should not exclude consideration of common underlying causes of food insecurity acting at the household scale, as illustrated here. The majority of household respondents who had reported not having enough to eat in the month prior to the interview also exhibited below average harvesting frequencies. Nonetheless, due to the complex spatial and temporal dynamics of wildlife ecology and determinants of human-wildlife interactions (i.e. harvesting availability and access), the underlying mechanisms influencing harvesting participation and success can differ

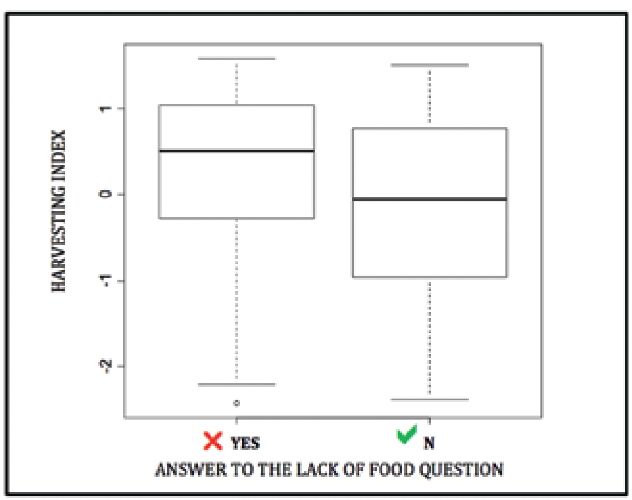

Figure 4. Boxplots illustrating the distribution of individual scores from our harvesting index in function of answers provided to the question from the 2004 Qanuippitaa? Question "In the last month, did it happen that there was not enough to eat in your house?".

significantly between households, communities and sub-regions and should be taken into account in order to develop any new food security policy for Nunavik. This approach, analysis and results were presented to the Nunavik Nutrition and Health Committee this year and publication preparation and further communication to discuss the approach used here is ongoing with regional representatives.

Activity 8: Towards a multivariate understanding food security determinants and outcomes in Nunavik

Activity leads: Fillion, Furgal, Lucas

Objectives: 1, 2, 3

Food security is a complex and multidimensional phenomenon which can be influenced by a number of factors and which can be related to health in a number of ways. In order to understand the determinants of food security in Nunavik, we are revisiting the Qanuippitaa 2004 data to explore the different profiles of food security experiences among participants with the understanding that the determinants of food security may differ throughout the population. Men and women, of different age and in different situations, are likely to have different experiences of food security/insecurity. Understanding how the determinants of food security interact to create different food security profiles in the population will inform interventions for specific target groups and areas in this population and ultimately contribute to the development of a food security assessment tool that is more comprehensive and able to capture these differences that likely exist throughout the region and among sub-populations in Nunavik.

Among the Qanuippitaa 2004 variables documented, we selected the ones which are most likely to be environmental and social determinants of food security status as well as health and nutritional outcomes. We are using two multivariate statistical tools, multiple correspondence analyses and cluster analyses, to look at the different experiences that different groups of people have with food security and insecurity and to draw the different profiles co-existing in the group. Data analysis is currently underway and should be completed by March 2016. These analyses will then be submitted the NNHC for approval before being sent for publication. After presentation to the NNHC we will also present or communicate, as guided by the NNHC, to the Nunavik regional food security working group.

Activity 9: Food insecurity prevalence and food quality among Inuit pregnant women, a cause for concern?

Activity leads: Lucas, Pirkle

Objectives: 1, 2

The consequences of food insecurity in specific at-risk groups in the population, such as pregnant women, are of great concern, especially if accompanied by malnutrition. Inadequate nutrition during pregnancy increases the risk of obstetrical complications,

Table 3. Socio-demographic characteristics of Inuit pregnant women, baseline data of the Arctic Char Distribution Program (AC/DP) monitoring (n=130).

	Food Secure (n=30)	**Food Insecure** (n=100)	***P***
HFIA score	8.90±0.31	14.2±3.68	*<0.001*
Insufficient quality score	2.93±0.25	5.11±1.64	*<0.001*
Insufficient food intake score	4.97±0.18	7.29±2.10	*<0.001*
Socio-demographics			
Age (years)	26.30±5.52	24.32±5.12	*0.09*
Parity (no)	2.26±1.32	2.09±1.74	*0.64*
≥ 3 (%)	26.67±8.11	29.00±4.56	*0.06*
Gestational age at baseline visit (weeks)	15.76±6.03	16.66±6.64	*0.49*
Education (≥sec. school. %)	40.00±8.97	31.00±4.64	*0.84*
Married/common law (%)	73.33±8.11	79.00±4.09	*0.43*
Personal income (%)			*0.01*
<$20.000	13.33±6.23	24.00±4.29	
≥$20.000	36.67±8.83	13.00±3.38	
DNK/RTA	50.00±9.16	63.00±4.85	
Social assistance (%)			*0.75*
Not working. not receiving welfare	33.33±8.64	41.00±4.94	
Not working. receiving welfare	23.33±7.75	20.00±4.02	
Working. not receiving welfare	43.33±9.08	39.00±4.90	
Hudson coast (%)	40.00±8.98	59.00±4.94	*0.07*
Interviewed in fall[c]	43.33±9.08	53.00±5.01	*0.35*
Household characteristics			
Total no. of people	3.90±2.34	4.97±2.84	*0.04*
No. of adults	1.80±1.13	2.25±1.73	*0.10*
No. of children	2.10±1.65	2.72±1.84	*0.10*
Total no. hunters and fishers	3.70±2.82	2.69±2.53	*0.06*
No. hunters	1.73±1.39	1.26±1.22	*0.07*
No. fishers	1.97±1.47	1.43±1.37	*0.07*
Lifestyle indicators			
Current smokers (%)	80.00±7.33	92.00±2.72	*0.06*
Nb. cig./d	6.76±4.49	8.55±4.28	*0.07*
Cannabis during pregn. (%)	23.33±7.75	36.00±4.82	*0.20*
Alcohol during pregn. (%)	33.33±8.64	48.00±5.02	*0.16*
Binge drinking during pregnancy (%)	26.67±8.11	27.00±4.46	*0.97*

Arithmetic mean ± SEM

Chi-square test were used to analyze categorical variables and t-tests were used for continuous variables.

affects foetal growth and development, and increases the child's risk of developing chronic diseases in adulthood. Even if diet quality is imbricated in most food security questionnaires, few studies have assessed the relationship between food insecurity and an overall dietary quality index, such as alternate Healthy Eating Index 2010 (aHEI-2010).

This project sought to determine the association between food insecurity and the dietary quality index aHEI-2010 among pregnant women in Nunavik. Cooperation with an existing project in the region has facilitated the opportunity to link these efforts to this ArcticNet project as they are pursuing similar objectives.

Between September 2013 and April 2014, 130 adult pregnant Inuit women were recruited in Nunavik. Dietary intake and food insecurity were assessed through interviews by a trained research nurse. Information about food insecurity (in the past 30 days) was collected using the Household Food Insecurity Access Scale (HFIAS) and household hunger scale (HHS). Dietary intake was assessed using semi-quantitative food-frequency questionnaires with 108-items divided into two sections: 31 traditional food items and 77 market food items. The quality of dietary intake was determined by using a modified version of the aHEI-2010, i.e. without the alcohol component. The aHEI-2010 had 10-components (vegetables, fruit, whole grains, sugar-sweetened beverages and fruit juice, nuts & legumes, red/processed meat, trans fat, long-chain omega-3 (EPA+DHA), polyunsaturated fatty acid, sodium. Each component score ranged from 0-10 and the total score ranged from 0-100. A higher score indicated a more healthful diet.

Results

Most women (n=100, 76.9%) were food insecure, with 10.0% categorized as mildly, 15.4% moderately, and 51.5% severely food insecure (Table 3). Of those categorized as severly food insecure, 29 (22.3% of total sample) had the most severe form of food insecurity – hunger. Total aHEI-2010 scores were lower among food insecure women compare to food secure (P for trend <0.001). Total aHEI-2010 score was 50.2±1.5 for food secure, 43.9±2.6 for mildly, 42.5±2.1 for moderately, and 41.4±1.1 for severely food insecure (Table 4). Compared to food secure, women in food insecurity had lower scores for vegetables, fruits, nuts and legumes. We also noted among food insecure women a lower score for sugar-sweetened beverages and fruit juice, which indicated a higher consumption (Figure 5a,b,c).

Knowing that the diet and body composition of a pregnant woman can have significant implications on the future health of the child, the high rate of food insecurity among pregnant women in this study and the relationship with lower overall dietary quality index warrants specific attention. These results are being communicated to the regional health authorities and discussed in regards to their findings and learning about the use of the a-HEI-2000 tool in association with the HFIAS food security assessment tool.

Activity 10: Assessment of implementation fidelity of the Arctic Char Distribution Program in Nunavik

Activity leads: Pirkle, Gautier, Lucas, Furgal

Objectives: 1, 3

When reviewing the circumpolar food security literature we notice few reports of intervention evaluation. Without the documentation of intervention development, implementation and evaluation it is difficult to know what actions are have any effect on household food security status over time. As a result, it is challenging to influence policy change in positive directions in support of positive food support action. We have cooperated with another project team members have been working on to share resutlts and learning on an evaluation of a food security and contaminants minimization intervention in Nunavik.

Table 4. Adjusted dietary intake and aHEI-2010 score among Inuit pregnant women, baseline data of the Arctic Char Distribution Program (AC/DP) monitoring.

	Food Secure (n=30)	**Food Insecure** (n=100)	***P***
Dietary Intake			
Vegetables, servings/d	3.07±0.59	1.35±0.21	0.009
Fruit, servings/d	3.80±0.40	2.57±0.28	0.01
Whole grains, g/d	0.56±0.10	0.48±0.07	0.51
SSB and fruit juice, servings/d	2.00±0.33	2.77±0.20	0.05
Nuts and legumes, servings/d	0.33±0.08	0.10±0.03	0.01
Red/processed meat. servings/d	1.21±0.12	1.54±0.13	0.07
trans Fat, % of energy	0.17±0.03	0.18±0.01	0.70
Long-chain n-3 (EPA+DHA), g/d	1.28±0.37	1.23±0.19	0.90
PUFA, % of energy	5.18±0.39	5.53±0.23	0.44
Sodium, mg/d	2042±276	1630±91	0.17
aHEI-2010 score			
Vegetables	4.57±0.62	2.42±0.26	0.003
Fruit	7.60±0.59	5.00±0.31	<0.001
Whole grains	0.07±0.01	0.06±0.01	0.51
SSB and fruit juice	3.59±0.86	1.11±0.25	0.009
Nuts and legumes	3.03±0.72	0.88±0.19	0.007
Red/processed meat	3.09±0.55	2.98±0.32	0.86
trans Fat	9.97±0.03	10.00±0.00	0.25
Long-chain n-3 (EPA+DHA)	8.86±0.38	8.61±0.28	0.59
PUFA	3.97±0.49	4.34±0.26	0.51
Sodium	4.12±0.60	5.21±0.31	0.11
Total aHEI-2010 score	**48.9±2.0**	**40.6±0.7**	**<0.001**

Adjusted means using Propensity Scoring (Inverse Probability Weighting) ± SEM
Model adjusted for: age, energy intake (kcal/d), area of residence (Hudson bay vs. Ungava bay), education (4 years of highschool completed or less than 4 years), income (< 20,000; ≥ 20,000; unknown), alcohol consumed since beginning of pregnancy (y/n), marijuana consumed since beginning of pregnancy (y/n), current smoker since beginning of pregnancy (y/n), number of people in the house, number of hunters and fishers in the house.
P trend: based on linear trend contrast
*Mean values significantly different from Food secure (ANCOVA Tukey post-hoc tests P < 0.05).

In September 2011, the Nunavik Regional Board of Health and Social Services began the *Arctic Char Distribution Program (AC-DP) for Pregnant Women*. This program promotes the consumption of the fish Arctic Char – a traditional Inuit food that is nutritionally rich and relatively low in contaminants – by pregnant women living in villages of Nunavik, an area in Northern Quebec (Canada) inhabited predominantly by people of Inuit ethnicity. This intervention intends to reduce exposure to contaminants and improve food security in Inuit communities, both of which are important public health issues in the region. However, implementation of the program has been incomplete as it has not covered all intended geographic areas, and its environmental and financial sustainability are challenged. In the interest of learning about the implementation and effectiveness of a food security related program in an Inuit community we assessed the program's implementation based on data collected from program documentation, meeting minutes, field notes, and qualitative interviews with program recipients and implementers. The results of this implementation have now been communicated back to the Nunavik Regional Board of Health and Social Services and Nunavik Nutrition and Health Committee as of June 2015 and results are in the process of being finalized for publication. Themes emerging from a review and coding of these materials are discussed in light of the framework for implementation fidelity developed by Carroll et al. (2007).

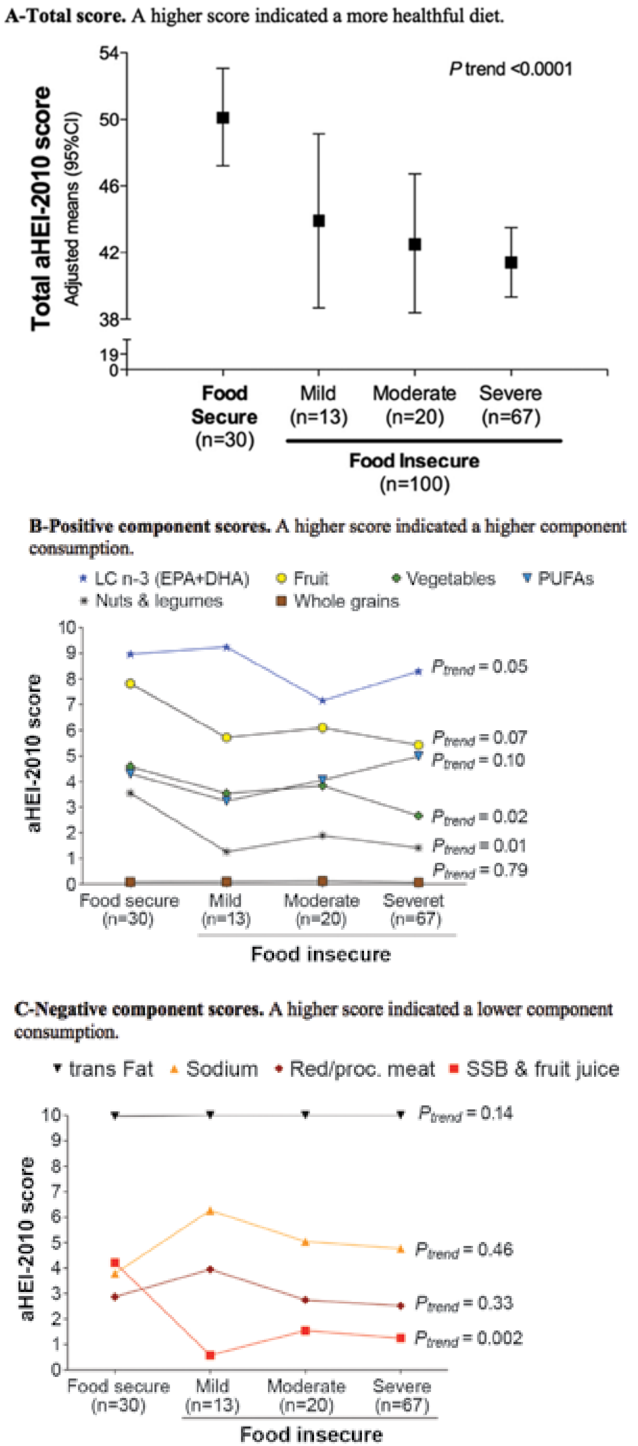

Figure 5a,b,c. Adjusted a-HEI-2010 total (A), positive (B) and negative (C) component scores among Inuit pregnant women, baseline data of the AC/DP monitoring.

Activity 11: Review of Nunavik regional policy landscape and food security priorities

Activity leads: Furgal, Thackeray

Objective: 3

To begin to understand the key issues and concerns related to food security in Nunavik, from the community's perspective, a review of the Parnasimautik documents was conducted in the summer of 2015 to identify and synthesize food security related content. The Parnasimautik process was a community consultation process held in all Nunavik communities to identify and discuss concerns related to development and the future of communities. This review and synthesis was done at the request of the Nunavik Regional Board of Health and Social Services in support of initial discussions to take place among members of the Regional Food Security Working Group that was formed in Nunavik in 2015. A review and power point presentation were provided to the NRBHSS and is currently under review.It is anticipated that a finalk version of this review will be presented to the NRBHSS this spring and presented to the Food Security Working Group shortly there after.

A literature review on food security policies and food and food-related policy has also been conducted as part of the MA thesis work of L Thackeray. This work will form the foundation for the policy and program review to be conducted in Nunavik this coming year in support of the Food Security Working Group discussions.

DISCUSSION

Despite the attention given to the issue of food insecurity in the Canadian Arctic today, as a result of the widespread challenges that exist and their implications for public health, significant gaps remain in our understanding of various aspects of the topic. To some degree, this challenges or hinders clear and effective action in the form of targeted interventions or appropriate policy responses. However, as we have shown with the systematic literature review conducted for this study there is a substantial and growing body of literature on this topic focused in the circumpolar North and much of it is the result of work focused in the Canadian Arctic. The remaining gaps however in this literature and the lack of information on the issues of political access and protection of political access to food, estimates of food availability, and assessments and understandings of biological quality of food as well as the status of food utilization knowledge and skills in Inuit communities require attention. This project is performing activities to learn about and advance our understanding on most of these topics.

A number of challenges and limitations have existed in our interpretation of food security prevalence levels reported for different communities or regions across the Canadian North in the past. This has been the result of a lack of previous validation of the widely, but inconsistently used USDA Household Food Security Survey Module in many Inuit communities (CCA, 2014). Our collection and review of a large number of existing food security assessment tools, based on a number of simple criteria associated with their applicability for the Inuit food context indicated that the significantly shorter Household Food Insecurity Access Scale (HFIAS) appears to address the largest number of priority areas applicable to the Inuit food context, more so than the commonly used USDA HFSSM. Further, through the use of an existing dataset of food security status among pregnant women in Nunavik, psychometric validation of the HFIAS tool indicates that it performs relatively well yet does not do as good a job at identifying individuals who are relatively food secure or very food insecure (e.g. hungry). This problem may be addressed though by replacing some questions on the HFIAS questionnaire with some questions about access to country foods.

The role of country food access and consumption on food security status in the validation of the HFIAS was also reflected in the further analysis conducted on the 2004 Qanuippitaa dataset from Nunavik to identify determinants of food insecurity in the region. Not surprisingly, however this is the first time the data has reflected this association to the best of our knowledge, this analysis identified that the level of participation in hunting and fishing activity reported by a household appears to have the strongest effect on their response to whether or not they lacked access to food in the month prior to the survey. Further, preliminary results from our food security assessment surveys in Nunatsiavut communities and Baker Lake, Nunavut, show significant differences in the levels of food insecurity from community to community, even within the same region. These and other data gathered under this project (e.g. results presented above) provide support for the argument that there are still many local factors that are more important in influencing the status of food security at the household level than regional or larger scale variables. This argues for more community level exploration and data as it appears as though food security could be, in large part, a ‘community’ phenomenon. The previous lack of examination of scale in previous research on the topic and reliance on Territorial or regional scale data has potentially minimized our understanding of the importance of such things as sharing networks, or individual household participation in hunting and fishing activities in food security status.

Despite the growing number of interventions developed and implemented to address Inuit food insecurity few initiatives have been evaluated in terms of their impacts on household food security status, and individual food behaviours (CPC, 2014; CCA, 2014). Work conducted in collaboration with this project has identified that in addition to exploring intervention impact we must also consider implementation evaluation to determine the extent to which an intervention functioned as intended. Further, the research conducted by our collaborators is also showing value of a nutritional categorization tool (a-HEI) when examining the impact of an intervention and the association between diet composition and food security status. As one might expect those that were found to be more food insecure also scored lower on the a-HEI indicating an impact on diet quality as well as quantity.

CONCLUSION

This project is taking a partnership and network approach to collaborating and working with various researchers engaged on different aspects of the issue of Inuit food insecurity. We are addressing identified gaps in understanding through examination of the literature, application of different statistical approaches to the analysis of existing datasets, evaluation of food security interventions and the tools used to do so where possible, the collection of Inuit perspectives and explanations of what it is and what it means to be challenged in accessing food on a regular basis (food insecure) and a review of and consultation with Inuit regional decision makers and those engaged in policy on the topic. Our learning to date has started to answer a number of outstanding questions on this topic and the focus of our research activities is proving valuable in yielding much needed data on certain aspects of the issue (e.g. scale of focus, determinants of food insecurity, tool validity and effectiveness, intervention impact) thus far.

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Mining Economies, Mining Families: Extractive Industries and Human Development in the Eastern Subarctic

Project Leader

Stephan Schott (Carleton University)

Network Investigators

Ben Bradshaw (University of Guelph)
Thierry Rodon (Université Laval)

Collaborators

Harry Borlase (Memorial University of Newfoundland)
Jean-Sébastien Boutet (Nunatsiavut Government)
Francine Couture (Nunatsiavut Government)
Theresa Hollett (Nunatsiavut Government)
Stas Olpinski (Makivik Corporation)
Betsy Palliser (Kativik Regional Government)
Jean-Marc Séguin (Makivik Corporation)

HQP

Anteneh Belayneh, Doctoral Student (Carleton University)
Deborah Nurse, Doctoral Student (Carleton University)
Caitlin Kenny, Masters Student (University of Guelph - Department of Geography)
Aboriginal Navigation of the Mine Permitting Landscape in Northern Canada
Laurence Lefebvre, Masters Student (Université Laval)

Northern HQP

Jason Dicker, Northern Research Staff (Kangidluasuk)
Molly Shiwak, Northern Research Staff (Nunatsiavut Government)

ABSTRACT

Our research project will provide a comprehensive, comparative review and assessment of the economic and human development impacts of major extractive industries in the Eastern Subarctic region. The main goal of the project is to establish a mining economic impact evaluation method, adapted to the North, that serves to appraise the local economic benefits resulting from the operating mines in Nunatsiavut and Nunavik. We will document, examine and interpret the experience of Québec-Labrador Inuit workers and entrepreneurs in relation to economic development and the regions' mining sectors. We will conduct surveys to assess the economic links and revenue flows between the Voisey's Bay and Raglan mines and local households and businesses. We will investigate the dynamics between the land-based and mining-based economies in Nunatsiavut and Nunavik by analyzing household spending and employment behaviour. Based on our analysis, we wish to contribute to the development of sustainable mining policies for the Eastern Subarctic and for the Canadian North more generally. The proposed research will address gaps in follow-up studies of large-scale mining activities, highlighting lessons from the experience of mineral developments in Nunatsiavut and Nunavik, and serving to construct an up-to-date, rigorous baseline that is indispensable for assessing, managing, and promoting the participation of Inuit jurisdictions in future extractive projects.

We believe that this research will contribute to a better understanding of economic impacts on Arctic and subarctic regions and on Inuit communities. It will be directly relevant to evaluate the impact of major mining projects on sustainable regional development and inform IBA negotiations in Nunavik, Nunatsiavut and elsewhere in the Canadian North.

KEY MESSAGES

- The role of extractive industries in development outcomes is an unsettled and contested research question (Bebbington et al., 2008; Graulau, 2008).
- The full scale of economic impacts linked to extractive industries is poorly understood and documented.
- The debate surrounding the role of northern mining in economic and social development remains very much unresolved.
- Understanding the link between mining development at different stages of the mine (exploration, construction, operation), local business development and household well-being is crucially important for the development of mining policies, human and sustainable development in Inuit regions.
- The research team will undertake a comprehensive review of the economic impacts of extractive industries in the Eastern Subarctic region of Nunatsiavut and Nunavik, with a focus on the two major mines currently operating in these jurisdictions: The Voisey's Bay mine and mill (Vale) and the Raglan mine (Glencore).

OBJECTIVES

- To establish a mining impact evaluation method, adapted to the north, that serves to appraise the local economic benefits resulting from the operating mines in Nunatsiavut and Nunavik;
- To model the dynamics of local business activities and mining activities in Nunatsiavut and Nunavik;
- To investigate the dynamics between the land-based and mining-based economies in Nunatsiavut and Nunavik;

- To document, examine and interpret the experience of Québec-Labrador Inuit workers and entrepreneurs in relation to economic development and the regions' mining sectors;
- To provide a comparative analysis of economic and mining developments in Nunavik and Nunatsiavut; and
- To learn from different experiences with the mining industry in both regions and identify insights for more successful mining policies and impact benefit and resource rent negotiations.

INTRODUCTION

Large-sale industrial projects, such as mineral extraction, are reported to bring economic benefits to Arctic and subarctic communities, in terms of accessing wage employment, encouraging training and skills acquisition linked to the industry, favoring the growth of entrepreneurial initiatives, securing transfer payments and royalties, and providing people with greater flexibility and autonomy associated with enhanced socioeconomic status (Government of Canada et al., 1999; Haley and Fisher, 2012). Industry-driven development can also be beneficial in the longer term due to economic diversification, inter-sectorial linkages and growth stimulation in other areas of the local economies touched by extractive activities (Eggert, 2001; Di Boscio, 2010; Fleming and Measham, 2014; International Council on Mining and Metals, 2012). These advances are mediated and supported by corporate social responsibility initiatives associated with community investments, monitoring programs, sustainability-based environmental assessments, and impacts and benefits agreements (IBA) signed between industrial and Aboriginal parties (Azapagic, 2004; Gibson, 2006; Fidler, 2010; Prno and Slocombe 2012).

Yet, non-renewable resource exploitation can also lead to an increase in income inequality within communities, may inhibit critical human, social and cultural capital, and has the potential to leave behind a harmful legacy on the land (Kniivilä, 2007; Sandlos and Keeling, 2012). Resulting changes to the territory, lifestyles, and livelihoods thus present potentially adverse effects for the individuals, households and communities affected by these developments, threatening to disrupt the delicate balance and tight interrelations that are characteristic of mixed economies in the north (Bernauer, 2011; Haunser et al., 2011; Rodon and Schott, 2014).

Overall, the role of extractive industries in development outcomes is an unsettled and somewhat contested question (Bebbington et al., 2008; Graulau, 2008). Most of the available evidence is based on regional or national studies in the developing south where researchers have directed their efforts. Yet development models have shown to be particularly inadequate for capturing the complexity of intra-community and intra-household dynamics (Hinojosa, 2013), as well as integrating the geographic specificity of Arctic and subarctic economies affected by non-renewable resource activities. As a result, the full scale of impacts linked to extractive industries has been poorly documented, and the debate surrounding the role of northern mining in economic and social development remains very much unresolved.

In 1999, between the signature of the Nunavik and Nunatsiavut agreements, nine Chief Executive Officers of the world's largest mining companies came together in Davos, Switzerland, and voiced their concern that their "social license to operate" was in jeopardy. Working through the World Business Council for Sustainable Development, they subsequently commissioned the International Institute for Environment and Development (London) and its North American partner, the International Institute for Sustainable Development to undertake a review of practices related to mining and mineral development. In their final report, the authors identify seven key components for a framework to assess the sustainability of the mining industry worldwide. The seventh component, synthesis and continuous learning, proposes to evaluate mines' contribution to sustainable development, formulating the overarching question:

"Does a full synthesis show that the net result will be positive or negative in the long term, and will there be periodic reassessments?" (International Institute for Sustainable Development, 2002, 11). Researchers and practioners have indeed recognized follow-up studies as an essential part of resource development projects, allowing for an objective evaluation of environmental assessment and impacts and benefits agreement processes, in terms of their predictive value, the effectiveness with which mitigation measures are implemented, and the suitability of the compensations granted via the negotiated agreements (Marshall et al., 2005). By producing an economic account of two active mines in the Eastern Subarctic, the proposed research will address gaps in ex-post analysis of large-scale mining activities, highlighting lessons from the experience of mineral developments in Nunatsiavut and Nunavik, and serving to construct an up-to-date, rigorous baseline that is indispensable for assessing, managing, and promoting the participation of Inuit jurisdictions in future extractive projects.

ACTIVITIES

We started our research project with a workshop in Quebec City on May 13/14 2015. At the workshop all researchers, newly hired research assistants and major collaborators that represented the Nunatsiavut Government and Makivik Corporation were present. We decided on the sequence of steps for the study and allocated various research sub-components to different groups.

From May-October 2015 a thorough literature review was conducted on the impacts of extractive industries on business development. During this period all the appropriate ethical clearances from the Nunatsiavut Government and from Carleton University were obtained. During this period appropriate business owners were identified in both Nunatsiavut and Nunavik to conduct focus groups. The focus group participants were selected with the assistance of the Nunatsiavut Government and Makivik Corporation. With the help of our findings in the literature review we designed questions for our focus group sessions. We presented our literature review and a draft of the focus group questions at the RESDA (Resource and Sustainable Development in the Arctic) Workshop in Kuujjuaq on October 22nd.

In June, Ben Bradshaw was invited to speak as a keynote at Expo Labrador in Happy Valley Goose Bay on the future of Aboriginal Engagement in the mining sector. This trip was used to meet with officials from the Nunatsiavut Government (NG) to operationalize plans to document the strategies employed by the Labrador Inuit in the permitting of the Voisey's Bay mine.

From October 21st-October 28th our research team conducted the field work component of our research. We conducted focus group sessions with business leaders in Kuujjuaq, Quebec. The focus groups had participants that were business owners in Kuujjuaq, Happy-Valley Goose Bay and Nunatsiavut. Business leaders from Nunatsiavut and Happy-Valley Goose Bay were flown in for these sessions. In addition, one researcher flew to Salluit, Quebec to conduct a focus group session with business owners who were unable to make the trip to Kuujjuaq. We also organized a networking event for all the business leaders from Nunatsiavut, Goose Bay and Kuujjuaq to share experiences with business development around the mining sector. This was the first time local businesses from both regions got together.

After our field trip to Kuujjuaq the research team spent time summarizing the results from the session with the participants. The results were summarized and sent to all the participants for feedback and to insure that nothing was omitted. The results of the focus group sessions are essential for the design of a business survey that will be distributed to all businesses in both Nunavik and Nunatsiavut.

On December 12th, 2015 the research team presented at the ArcticNet Annual Scientific Meeting in Vancouver, British Columbia. The research team was part of a session on Extractive Industries and Indigenous Communities which was chaired by the Principal Investigator Prof. Stephan Schott. Prof. Thierry Rodon and Prof. Ben Bradshaw were also presenters at this session that sparked a discussion on the relationship between the mining industry and economic development in the Canadian subarctic.

RESULTS

Our key informant interviews with officials of the Nunatsiavut Government revealed a number of strategies employed by the Labrador Inuit to realize their interests and maximize socioeconomic outcomes in the permitting and development of the Voisey's Bay mine. For the Labrador Inuit, the proposed mineral development 35 km southwest of Nain was recognized as holding significant potential to create socioeconomic benefits at a time when opportunities in the fishing industry were in decline. At the same time, the proposal generated several concerns for the Labrador Inuit. One prominent concern centred on sea ice breakage as a result of winter shipping. Another centred on the possible erosion of traditional subsistence lifestyles, especially given the potential for further loss of culturally significant species like caribou. Given this, the Labrador Inuit sought to find a path forward that would maximize local socioeconomic benefits and minimize ecological and cultural impacts. They did so through the strategic use of multiple, parallel planning processes including Modern Land Claim Agreements, Impact and Benefit Agreements, Environmental Assessment and, on occasion, litigation. The result of this was that the Labrador Inuit were able to effectively exercise their authority and co-develop a project that would benefit the modern Inuit market economy without significantly harming traditional economies or values. Operational for 10 years with a greater than 50% Inuit and Innu employment rate, the Voisey's Bay mine is rightly regarded as an exemplary case of large scale development conceived in partnership with its territorial hosts.

Our focus group sessions revealed several insights into the relationship between the mining industry and businesses in Nunavik and Nunatsiavut. Before conducting the focus groups our focus was mostly on the differences that would occur between the construction and the operational phases of the mine. What was apparent from meeting the businesses that were selected for the focus group sessions, both from Nunavik and Nunatsiavut, was that the businesses dealt with the mines primarily in the exploration phase of mine development. Specific results from the focus groups are organized under a number of headings that reflect our key insights.

Competition for Labour

In looking at the literature one of the things we identified as a point of interest was whether there was competition for qualified labour due to the presence of mining. The literature pointed out the fact that due to the higher wages in the mining industry companies in other industries had a hard time finding qualified personnel. The session with the businesses from Kuujjuaq revealed that there were not a lot of qualified personnel before the Raglan Mine opened. The businesses also felt there was no difference in access to labour at any stage of the mine's development. One business pointed out that it is hard to find qualified personnel at the mine because people would rather work in town than at the mine because of the length of shifts (two weeks).

When the businesses from Nunatsiavut were asked about competition for labour they mostly highlighted how training of personnel is a big issue in Nunatsiavut. Due to a lack of training there is a limit to how many people can take advantage of opportunities. One of the challenges is that some of the training programmes are in Goose Bay and once people move to get training there, they may not return due to the housing shortage in the Nunatsiavut communities. They also pointed out that training was a regional issue that never really got off the ground until the mine was in its operational phase.

Businesses from Goose Bay emphasized the need to have better funding and training opportunities. Greater recognition by the NG of the training and formation offered by the businesses would be appreciated by the businesses from Goose Bay. In addition it would be great if the rules around accreditation for training were relaxed.

The focus group with businesses from Salluit revealed that support for training programs comes from the Kativik Regional Government (KRG). They also revealed that the land holding corporation is involved in providing accommodation and logistics for training purposes.

The focus group session with the businesses from Goose Bay also revealed that local businesses are not able to compete with the mining industry with respect to salaries and working conditions. They mentioned that those who work at the mine work more or less six months a year and make a good salary, so they can buy a big house, snowmobile, etc. In addition, they mentioned that the turnover rate is low for employees working at the mine. This seems in stark contrast to the experience at the Raglan mine in Nunavik.

Impact on community and business development

Businesses from Kuujjuaq all agreed that mining has been generally positive but mentioned that impacts are lessened the farther away the community is from the mine. Recently this has changed as communities further away from the mine increasingly supply business services and employees to the mining site. The pool of employees is limited based on nearby communities with high turnover rates and stricter workplace policies. They were talking about the "mining industry" as opposed to just Raglan and they stated that it has become 'more and more' positive. Business leaders pointed to the improvements in infrastructure, employment and shipping. They also pointed out that mining companies are more cognisant of the environmental concerns of communities and their relationship to the land. The level of communication has apparently improved even though there are challenges and the mining companies are aware of how they are perceived and are eager to have a good reputation and acceptance in the communities.

Businesses from Nunatsiavut also agreed that mining has generally been positive. They did point out that when Voisey's Bay started everyone had an expectation of finding a job and it didn't really happen. The expectation still exists with respect to the underground expansion of the mine as well. It was mentioned that wages decreased as the mine moved past the exploration phase for people working in the Nunatsiavut communities.

Businesses from Goose Bay and the NG agreed that money is flowing back to the community. Infrastructure and buildings are built because of the contracts Inuit companies have with the mine. A lot of shipping businesses are positively impacted by the mining activity as well according to those participants. The fact that the salaries in the mining sector are higher makes people travel more (by boat and plane), which is a nice side effect of the mining activity according to the participants. Both businesses from Nunatsiavut and Goose Bay highlighted that workers who find employment due to mining are not always able to find permanent jobs (seasonal in most cases).

Focus group sessions with Salluit revealed that profits have declined due to tougher negotiation tactics by companies as a result of the decline in the price of nickel. These sessions also revealed that people are not working as much. Again the driver seems to be the price of nickel and the businesses highlighted that the community is not prepared for the fluctuation of prices. The landholding corporation did state that they have tried to diversify but the recent downturn in mining is something new. With respect to impacts on the community the businesses highlighted the incomes that employees make and the increase in tax revenue.

Mining does not seem to have impacted new business development in Salluit according to the participants unless the businesses have partnerships with established businesses from elsewhere. Participants also mentioned that there were not many businesses in Salluit.

Relationships with Provincial governments

During the focus group sessions with businesses from Kuujjuaq some people highlighted the lack of support they receive from the Quebec Government. The businesses want the government to recognize Inuit businesses. There was a concern that Plan Nord would benefit southern businesses. One business pointed to the fact that Nunavik was the only place where no preference was given to Inuit businesses.

Businesses from Nunatsiavut highlighted the need for some support from the NG to let mining companies know what local businesses offer; for example: what they do and what their capacities are and how long they have been in business. The need for better advertisement was identified. Apparently the Innu are more forceful than the NG in this department according to one of the business owners. The businesses from Goose Bay also stated that more collaboration between the local businesses in Nunatsiavut and businesses in Goose Bay would be positive. They reiterated that it would be beneficial if mining companies would provide regularly updated lists to the local businesses regarding its plans for subcontracting. This list would allow businesses to bid for contracts with more preparation and demonstrate their capacity to contribute.

Experiences with the mining companies

In Nunavik local businesses from Kuujjuaq mentioned that it was more personal to deal with Canadian Royalties rather than with Glencore's head office.

The turnover rate of employees in the mine seems to be larger at Raglan mine than at Voisey's Bay. Local Nunavik businesses reported that it was difficult to recruit employees for the mine from the nearby communities. A new business sector, therefore, developed to recruit employees from all the other communities in Nunavik. The situation seems quite different in Nunatsiavut where employees tend to stay longer at Voisey's Bay and a larger portion of Vale's Inuit employees fly in from the major hub Goose Bay and move from their home communities in Nunatsiavut to Goose Bay.

Businesses from Goose Bay and the NG pointed out that many qualified personnel aren't able to find a full-time job. They said there was significant funding from the government for training for mining jobs, but these programs have not necessarily translated into permanent jobs. There are also computerised simulation programs that have been put in place to prepare the community members to work at the mine. A good aspect of this training program is that it takes place in the community (in comparison to the training that is done on the Raglan site in Nunavik). This is important for the people that wish to be engaged in traditional community activities. Nevertheless, it is difficult for workers to find permanent jobs as a lot of the jobs that are available are seasonal in nature or available during the construction phase of the mine.

Business officials from Nunatsiavut mentioned that it is quite costly and challenging for small local businesses to adapt to a change in ownership of a major mine like Voisey's Bay. Another challenge is the retention of well-trained employees when business activities fluctuate due to different stages of the mine operation and commodity price fluctuations. It is difficult to rehire well-trained employees that move away when there is a temporary slowdown.

Recently the bidding process in Nunatsiavut has become more competitive, and Vale has more stringent safety guidelines and requirements. There are more opportunities to partner up but partnerships are risky, and the wrong partnerships can permanently ruin the reputation of a small local company. One challenge raised in both Nunavik and Nunatsiavut is that there is a lack of interpersonal relationship with the mining companies. Most communication is centralized via E-mail or at best by phone.

Interestingly the focus groups revealed that there is no requirement for companies in the exploration stage to use local businesses. Giving contracts to Inuit businesses during the exploration phase is not part of the IBA. This point was brought up by businesses from Nunatsiavut.

The businesses from Salluit mentioned costs of equipment and how the equipment is both very expensive and specialized. Instead of investing in equipment that they felt they would use only a few times they thought it was beneficial to invest in labour and training programs. Training is sometimes in Montreal or outside the community and people are not always keen on leaving their communities. With respect to support from mining companies the businesses from Salluit mentioned that they need to contact mining companies for donations. The support for training programs from Raglan has increased recently and they have agreed to donate five simulators. The training support program is geared towards the entire region and not just Salluit.

DISCUSSION

Our preliminary analysis after eight months into the research project indicates that there are significant differences in the experiences and negotiations with the two major mining companies (Glencore in Nunavik and Vale in Nunatsiavut). While Vale achieved more than 50% Inuit employment, Glencore reached only 18% of employment at the mine. The supply chain in both cases also seems to be different. Goose Bay seems to have emerged as a major hub for local Inuit owned businesses to supply mining needs, while it is more dispersed in Nunavik. This might have caused

more migration from traditional Inuit communities to a major centre outside of Nunatsiavut than in Nunavik. It is well possible though that many Inuit businesses in Nunavik operate out of Montreal, where for example the FCNQ of Nunavik has its headquarters.

Our discussion with business leaders from both regions also indicates a common challenge. Local businesses in both regions struggle with the involvement in the supply chain at the operation phase of the mine. They need to partner up with Southern companies that conduct business at a larger scale. How to maximize Inuit business shares, employment and engagement remains a challenge that needs to be further addressed. In addition there are information and communication hurdles with the bidding on available contracts and with the clear understanding of what the mining companies require at what stage of mining development. This is where local governments and mining companies can play a more active role.

CONCLUSION

Our comparative analysis provides us with many important lessons and questions for the economic development in Arctic regions that interact with mining companies. Talking to local entrepreneurs and government officials is essential in comprehending the complexity of the issues. Our next steps will be to continue the discussion with more in-depth interviews, a comprehensive quantitative and qualitative survey for businesses in both regions, and to commence our discussion with mining employees and households. Mining is and will play a major role in Northern communities. In order to get the most out of mining activities for Northerners and their communities we need to better understand what the potential economic benefits are and how they can be maximized. Our understanding of the dynamics of mining activities, local business creation and development, as well as household well-being and the impacts on subsistence harvesting is very limited. This makes it difficult to negotiate with major mining companies and to specify proper objectives and policies for local and regional governments. With our project we wish to contribute to a better understanding of this subject and to start a very necessary, open and transparent conversation.

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SECTION V. KNOWLEDGE TRANSFER

Section V is composed of four ArcticNet research projects focussing on knowledge mobilization in support of sustainable management and development in the Canadian Arctic.

Knowledge Co-Production for Sustainability in Canadian Arctic Coastal Communities

Project Leaders

Trevor Bell (Memorial University of Newfoundland); Donald Forbes (Natural Resources Canada - Geological Survey of Canada)

Network Investigators

David Atkinson (University of Victoria)
Thomas James (University of Victoria)
Gita Ljubicic (Carleton University)

Collaborators

Helene Amundsen (CICERO)
Leah Braithwaite (Environment Canada - Canadian Ice Service)
Nicole Couture (McGill University)
Jackie Dawson (University of Guelph)
Shelly Elverum (Ikaarvik)
Christian Haas (York University)
Gleb Kraev (Russian Academy of Sciences)
Gavin Manson (University of Guelph - Department of Geography)
Elizabeth Marino (Oregon State University)
Joan Nymand Larsen (Stefansson Arctic Institute)
Paul Overduin (Alfred-Wegener Institute Helmholtz Centre for Polar and Marine Research)
Alison Perrin (Yukon College)
Andrey Petrov (University of Northern Iowa)
Peter Pulsifer (Inuit Tapiriit Kanatami)
Tom Sheldon (Nunatsiavut Department of Lands and Natural Resources)
Tatiana Vlasova (Russian Academy of Sciences)
Dustin Whalen (Natural Resources Canada - Geological Survey of Canada (Atlantic))

HQP

Laura Eerkes-Medrano, Doctoral Student (University of Victoria)
Vida Khalilian, Doctoral Student (University of Victoria)
Synoptic drivers of fog and low visibility events on the coastal regions of northern Canada
Rudy Riedlsperger, Doctoral Student (Memorial University of Newfoundland)
Labrador's Lifelines: Assessing community vulnerability to changes in routes and trails
Norman Shippee, Doctoral Student (University of Saskatchewan)
Development of seasonal outlooks for storminess parameters, Canadian and Alaskan North
Katherine Wilson, Doctoral Student (Memorial University of Newfoundland)
Ben Bagnall, Masters Student (Memorial University of Newfoundland)
Spatial hazard mapping in Arviat, Nunavut
Beth Cowan, Masters Student (Memorial University of Newfoundland)
The submerged sea level lowstand of Cumberland Peninsula, Baffin Island, NU
Merran Smith, Masters Student (Memorial University of Newfoundland)
Lake Melville Sea Ice Project: analyzing change and mapping sea ice use to inform monitoring and safer travel for Labrador Inuit
Adam Wicks, Masters Student (University of Victoria)
Robert Briggs, Research Associate (Memorial University of Newfoundland)

Scott Hatcher, Research Associate (Memorial University of Newfoundland)
Cassandra Lee, Technical Staff (Memorial University of Newfoundland)
Christina Robinson, Technical Staff (Memorial University of Newfoundland)

Northern HQP

Joey Angnatok, Northern Research Staff (Community of Nain)
Andrew Arreak, Northern Research Staff (SmartICE)
Ancilla Irkok, Northern Research Staff (Arviat Wellness Centre/ Youth Climate Monitors)
Kelly Kigusiutnak, Northern Research Staff (Arviat Young Hunters Program)
Rodd Laing, Northern Research Staff (Nunatsiavut Government)
Jamie Okatsiak, Northern Research Staff (Arviat Wellness Centre/ Youth Climate Monitors)
Shirley Tagalik, Northern Research Staff (Hamlet of Arviat)
Hunter Tattuinee, Northern Research Staff (Arviat Young Hunters Program)

ABSTRACT

The goal of this project is to develop a network of community knowledge centres, accessible and relevant to northern residents, that supports monitoring and analysis of environmental and social conditions to meet information needs for local and regional planning, while addressing local priorities. As the Canadian component of a larger, circumpolar, coastal communities network (CACCON), this project will complement and enhance existing community- and regional-based initiatives, facilitating peer-to-peer communication and knowledge-sharing with partner centres around the Arctic. Specifically, the project will support key components of ongoing and future observing and change detection functions, including marine climate (winds, waves, sea ice), visibility (fog, blowing snow, smoke), coastal hazards (breakup and storm-surge flooding, shoreline erosion, ice pile-up, local tsunami risk), and landscape hazards (slope failure, active-layer deepening, excess ground ice and thaw consolidation), supported by digital imagery and mapping data. These initiatives address a broad range of challenges and information needs for transportation, built infrastructure, healthy homes, preservation of culturally important sites, safe sea-ice travel, and food security in northern coastal communities.

KEY MESSAGES

- The Circumpolar Coastal Communities Observatory Network (CACCON) has been launched as the Arctic Regional Engagement Network of Future Earth Coasts. Co-design activities have been underway throughout the year across northern Canada and with international partners and communities.
- Many challenges to sustainability are near-universal and amenable to common adaptation strategies, which can be developed by sharing experience, innovation, and insight across the network. At the same time, local priorities and additional issues raise place-based knowledge requirements and highlight the need for co-production and co-design of sustainability initiatives.
- SmartICE addresses a community priority for timely sea-ice information to support safe travel. Designed to augment local sea-ice knowledge, not replace it, SmartICE comprises remote and mobile sea-ice thickness sensor data combined with ice hazard mapping from satellite imagery disseminated through a community data portal.
- The SmartICE project is a community-academic-government-industry collaboration that was first developed in Nunatsiavut communities and is now expanding to Nunavut with Labrador Inuit working alongside and training Inuit from Pond Inlet.
- The Cost-of-Adaptation Mapping (CAM) project responds to the information needs of northern communities by revealing the costs and benefits of adaptation choices in the selection and preparation of building land and the design and construction of community infrastructure. It is intended to augment local knowledge and expertise while strengthening capacity to make effective community-centred, climate-adapted infrastructure choices.
- The CAM project is being piloted in Arviat (NU) and old Crow (YK). It builds on the hazard and vulnerability mapping in these communities by using their map products as the basis to show how adaptation actions can make more community land available for infrastructure development.
- Decision-tree mapping is revealing the processes by which decisions on building land development, lot preparation and foundation selection are being made and implemented in Arviat. It identifies the entry points through which geoscience knowledge can have the greatest benefit for the development of sustainable infrastructure in Arviat and other Nunavut communities.

- Canada's coastal archaeology is at risk to the impacts of rising sea level. The *Coastal Archaeological Resources Risk Assessment* (CARRA) project addresses the needs of heritage managers for tools and best practices to respond to an ever-increasing number of at-risk sites in coastal Canada.
- Measurements of sedimentation and subsidence in the Mackenzie Delta suggest that the outer delta is not maintaining pace with rising relative sea level. Preliminary work suggests that as much as 26% of the outer delta land area today (important bird nesting habitat) may be permanently inundated by 2085.
- Coastal erosion in the southeastern Beaufort Sea (Inuvialuit Settlement Region) produces some of the most rapid shoreline retreat in Canada, threatening coastal community infrastructure, navigation infrastructure, subsistence camps, archaeological sites, and important habitat. Project members are providing geoscientific support to the Inuvialuit Land Administration in its evaluation of adaptation options.
- Input was provided to the Arctic Council's Adaptations Actions for a Change Arctic (AACA) regarding community observation of natural phenomena; project members contributed sections to a new publication focusing on all aspects of the Bering-Chukchi-Beaufort Sea coastal area.
- The vulnerability of subsistence infrastructure in Iqaluit has been demonstrated by recently published results on coastal hazards. Although this infrastructure is an essential contributor to food security in the community, it has not previously received much attention in the planning process. Urban development on the landward side limits options for setback and relocation away from the waterfront is impractical.

OBJECTIVES

The overarching goal of this project is to pilot the development of a network of community knowledge centres, accessible and relevant to northern residents, that provide the capacity for integrated situational monitoring and analysis of physical/ecological and social conditions at local and regional levels, attentive to local priorities. A number of specific milestones were identified for the first year of the new project, including:

- Launch of the Circumpolar Arctic Coastal Communities Observatory Network (CACCON) and Arctic Regional Engagement Network of Future Earth Coasts.
- Co-design meetings and knowledge centre development in partner communities.
- Development and pilot application of environmental, social, and integrated situational indicators.
- Permafrost terrain type classification for Arviat.
- Integrated systems test and deployment of *SmartICE* sensor system.
- Fog and low visibility analysis, western Canadian Arctic.
- Seasonal predictive capacity for operational weather hazards, western Arctic.
- Ten-year compilation of Mackenzie Delta breakup newsletter.

Progress on project objectives is reported below under the following themes:

- Circumpolar Arctic Coastal Communities Observatory Network (CACCON)
- Sea-ice Monitoring and Real-time Information for Coastal Environments (SmartICE)
- Cost-of-Adaptation Mapping (CAM)

- Coastal Archaeological Resources Risk Assessment (CARRA)
- Coastal Flooding and Erosion Hazards
- Coastal Climate and Weather Hazards
- Sea-Level Projections

INTRODUCTION

Canadian Arctic and sub-Arctic Inuit communities are almost exclusively located in coastal settings that provide access to marine and terrestrial food resources, transportation and communication corridors, and culturally significant landscapes. These coastal communities and their critical infrastructure are also exposed to a range of coastal and marine hazards in addition to landscape hazards common throughout the permafrost regions of Canada. The coastal zone is the locus of complex interactions among marine, terrestrial, and atmospheric processes and thus is particularly sensitive to ongoing and projected environmental change, exacerbated by anthropogenic stressors (Forbes 2011). Combined with challenges of economic and social development, demographics, globalization, mixed cash and non-cash economies, maintenance of linguistic and cultural integrity, health, and well-being, the already-noticeable effects of environmental change are an added source of uncertainty and concern. Coastal archaeological sites in Arctic Canada are also under threat, with important knowledge of the region's history and prehistory potentially lost to erosion. Climate change will exacerbate existing coastal hazards, leading to more rapid loss of archaeological resources and culturally significant sites in the future. All of these factors represent potential vulnerabilities and challenges to health and safety, community resilience, cultural integrity, sustainability, and well-being. This project is based on the conviction that an integrated, collaborative, and holistic approach to monitoring, understanding, and managing the many sources of change in northern communities is a key to local empowerment and sustainable development for present and future generations.

ACTIVITIES

CACCON

(Bell, Forbes, Amundsen, Couture, Eerkes-Medrano, Kraev, Manson, Nymand Larsen, Overduin, Petrov, Pulsifer, Riedlsperger, Vlasova)

- The Circumpolar Arctic Coastal Communities Observatory Network (CACCON) was launched in April 2015 at the Third International Conference on Arctic Research Planning (ICARP-III) in Toyama, Japan. CACCON was featured in three panel sessions (see caccon.org and #CACCON).
- Co-design meetings and preliminary co-production activities took place in Arviat, Pond Inlet, and Nunatsiavut during this first year, with further meetings planned in Iqaluit, Clyde River, and the Inuvialuit Settlement Region before fiscal year-end.
- CACCON contributed by remote link to the Alaska A-OK initiating meeting in Fairbanks (July 2015), was featured at the Polar Data Forum in Waterloo (October 2015), contributed to the Community-Based Observing Networks workshop in Seattle (October 2015), and reported to the US Intergovernmental Arctic Policy Committee in Washington DC (December 2015).
- A side meeting at the Arctic Science Summit Week in Fairbanks (March 2016) will further advance the co-design phase with community representatives from Alaska and northern Canada (https://assw2016.org/content/caccon-circum-arctic-network-coastal-communities).
- A CACCON White Paper, prepared in collaboration with Future Earth Coasts, ELOKA, and the NSF-funded Research Coordination

Network Arctic-COAST, has been submitted to the Arctic Observing Summit (March 2016).

- Under the CanCoast initiative, a topologically consistent 1:50k vector shoreline has been developed for all of Canada using the CanVec v.9 data set from GeoGratis (Natural Resources Canada). This forms the reference vector for an index of physical shoreline sensitivity to climate change, which has been further refined over the past year.

SmartICE

(Bell, Ljubicic, Braithwaite, Dawson, Haas, Briggs, Wilson, Arreak, Angnatok, Laing, Sheldon, Elverum)

- The SmartICE project deployed successfully during winter 2014-2015 in Nain, Nunatsiavut, with both in-situ and mobile sea-ice thickness sensors.
- In partnership with the Canadian Ice Service, workshops with Search and Rescue (SAR) teams were conducted on sea-ice information needs in Nain and Rigolet.
- A beta version of the SmartICE, web-based, sea-ice information portal was developed by EMSAT for launch in the 2016 sea-ice season.
- Project consultations were held with 28 partners and collaborators in Pond Inlet and Iqaluit (November 2015) in preparation for initiation of SmartICE Pond Inlet.
- The Pond Inlet project team was established with hiring of Andrew Arreak as the community project coordinator partnered with *Ikaarvik: Barriers to Bridges*.

Cost-of-Adaptation Mapping (CAM)

(Bell, Forbes, Riedlsperger, Bagnall, Perrin, Lee, Tagalik)

- Fieldwork and community consultations continued in the project study communities of Arviat (NU) and Old Crow (Yukon).
- Surficial geology mapping and permafrost coring were undertaken in Arviat by the Memorial University team in the early fall. Analysis of field data is ongoing.
- Interviews were conducted with community and government decision-makers to understand and map the decision-making processes for selection of housing lots and the construction and design of gravel pads and house foundations in Arviat. The objective was to identify entry points for geoscientific knowledge.

CARRA

(Bell, Robinson, Lee, Storey, Belsheim)

- The CARRA team is developing climate-change adaptation tools, together referred to as *CARRAtools*, that identify, prioritize and present management options for coastal archaeological sites at risk of inundation by rising sea levels.
- One such tool, called *Sites@Risk,* is designed for heritage managers and others involved in assessing, managing, and maintaining coastal heritage resources.
- Through case study analysis, the team is determining current practices for prioritizing at-risk sites for management actions and examining potential options.

Coastal Flooding and Erosion Hazards

(Forbes, Atkinson, Whalen, Couture, Manson)

- The Mackenzie-Beaufort Breakup Newsletter was continued for the 10^{th} year, publishing at 2-3 day intervals during the 2015 breakup season (May-July), and distributed to a mailing list of well over 300.
- We continued to monitor subsidence and sedimentation rates in the outer Mackenzie Delta to evaluate the potential for land and habitat loss with a warming climate and accelerated sea-level rise.

- NRCan collaborators monitored coastal erosion with repeat surveys at eight sites in the Yukon and 14 sites in the Northwest Territories, and established a new site for GNWT at Cape Bathurst. Time-lapse cameras were installed to document erosion processes at Tuktoyaktuk Island and three other sites with rapid coastal retreat.
- Survey and sampling activities in and adjacent to Tuktoyaktuk Harbour addressed the long-term viability of the port, an issue of major concern for Transport Canada, the Inuvialuit Lands Administration, and the local community.
- A new synthesis of recent work on sea-level projections and coastal hazards in Iqaluit was shared with local practitioners for incorporation into the urban planning process.

Coastal Climate and Weather Hazards

(Atkinson, Eerkes-Medrano, Shippee and others)

- Three communities in the Inuvialuit Settlement Region (Sachs Harbour, Tuktoyaktuk, and Ulukhaktok) participated in the 2015 work on adverse marine weather, co-supported by MEOPAR and Transport Canada.
- Participants from coastal communities, industry, marine transportation, and operation/emergency response groups identified specific occurrences of problematic weather or wave events that have interfered with their activities.
- These occurrences were linked to broader atmospheric patterns to make the large- to local-scale connections needed to forecast weather at the local and operational scale.

Sea-Level Projections

(James, Forbes and others)

- Up-dated projections of 21st century sea-level rise for 22 sites in the Canadian Arctic were published in a 2014 Open File report (James et al. 2014). During the past year, a tabulated version was released (James et al. 2015). Suitable for digital access, this facilitates estimates of sea-level change at decadal intervals to 2100.

RESULTS

CACCON

The Circumpolar Arctic Coastal Communities Observatory Network (CACCON) was formally launched in April 2015 and designated later in the summer as the Arctic Regional Engagement Network of Future Earth Coasts. CACCON is envisaged as a distributed network of local (community or regional) knowledge centres exchanging information (data, technical capacity, adaptation strategies, other types of knowledge) locally and with one another (Figure 1), supported through a common coordination office with web and other resources at Memorial University.

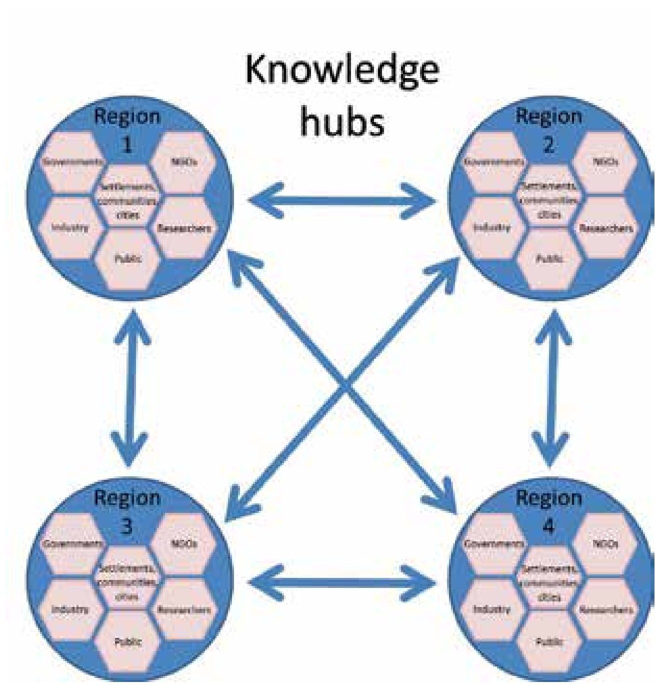

Figure 1. Schematic distributed network structure for CACCON, with interacting community or regional knowledge hubs.

The current configuration of the network in the North American Arctic is shown in Figure 2, with potential future expansion indicated in grey.

The true test of CACCON is progress in the development of knowledge management and dissemination capacity at the local level. One size may not fit all and there are many existing initiatives that contribute pieces to the puzzle. Bringing these disparate strategies together with additional support mechanisms and knowledge sources to provide the information truly relevant to local or regional decision priorities is the goal embraced by CACCON. This requires a thorough assessment of current capacity in the context of existing initiatives and a prolonged co-design phase ramping up through the winter.

Initial work on indicators for promoting and measuring sustainability challenges and progress (Forbes et al. 2015a) recognizes capacity to adapt as a critical determinant of individual and community health, well-being, and resilience, but it depends on a number of key factors, including objectives (degree of consensus), perceptions of risk, and societal values, among others. Knowledge is the key to successful outcomes, but how do individuals and decision-makers identify and access the necessary and reliable knowledge to make the best choices in particular circumstances? Solutions-oriented research to enable proactive adaptation to environmental and social change is necessarily a collaborative effort depending critically on the recognition of local priorities, the direct involvement of those with strongest stake in the outcomes, and an effective foundation of local and relevant community-based knowledge (Johnson et al. 2015; Alessa et al. 2015). We are building on successful initiatives such as Ittaq in Clyde River, the Sustainable Communities initiative in Nunatsiavut, and the Arviat Wellness Centre to guide the evolution of the network.

CanCoast is a separate initiative with a Canada-wide perspective, but with close links to CACCON. As a preliminary CanCoast product, a Canada-wide classification of coastal sensitivity to climate change,

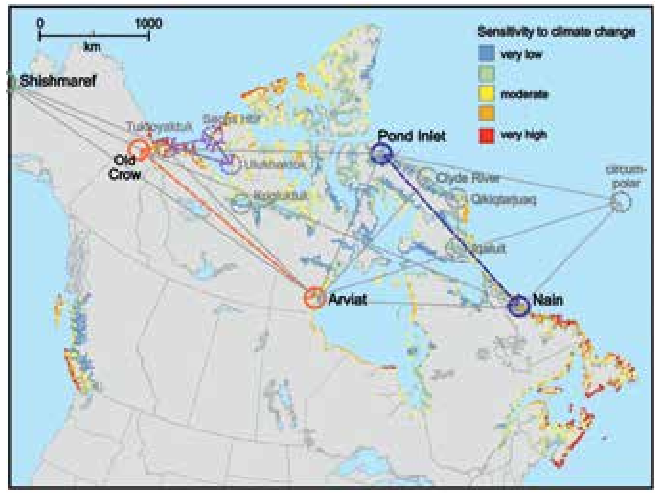

Figure 2. CACCON pilot knowledge centres (and potential centres) superimposed on CanCoast preliminary classification of coastal sensitivity to climate change. Strong community-to-community links are already developed between Nain and Pond Inlet (blue: SmartICE) and between Arviat and Old Crow (orange: Cost-of-Adaptation Mapping), and grey lines show some of the links in the overall network web (cf. Figure 1).

was developed (Figure 2) and contributed to the forthcoming Canadian coastal climate assessment (Lemmen and Warren 2016). The sensitivity index combines attributes of sensitivity to inundation, storm-surge flooding, and erosion. In the Canadian Arctic, the most sensitive coasts are in the Inuvialuit Settlement Region in the west, where crustal subsidence contributes to rapid sea-level rise interacting with highly erodible permafrost terrain (Couture 2015; Lamoureux et al. 2015). ISR communities such as Tuktoyaktuk and Sachs Harbour, as well as major subsistence sites such as Shingle Point (used by residents of Aklavik) are strongly affected. Crustal subsidence in the easternmost Canadian Arctic contributes to local erosion and inundation, although local progradation can occur if sediment supply is sufficient (Forbes et al. 2015b; St-Hilaire-Gravel et al. 2015). Most of the Canadian Arctic is dominated by residual postglacial isostatic uplift (James et al. 2014), often with rock or gravel coasts, resulting in low index of sensitivity, yet short-term rapid coastal realignment can occur (Forbes et al. 2015b).

SmartICE

SmartICE developed a new version of the in situ sea-ice thickness sensor (SmartSENSOR v.3) incorporating temperature and conductivity and a mechanism for deployment in open water. Hardware and software were upgraded for the SmartQAMUTIK mobile ice-sled-mounted ice thickness sensor and successfully deployed it in Nain (Figure 3). Deployment of SmartICE operations in Pond Inlet (Figure 2) will take place this winter in partnership with our community partner Ikaarvik. A preliminary sea-ice user workshop is planned for February in Pond Inlet, followed by training of community researchers in March and a full community sea-ice workshop in April. Katherine Wilson, a new PhD student on the project, has initiated her research project to investigate new frameworks for integrating traditional knowledge and western science methods through the SmartICE program.

Preliminary observations from a qualitative comparison of SmartICE surface data and Radarsat2 imagery around Nain suggest the following: (1) Ship tracks are relatively easy to pick out in all image resolutions at all times of year, but there is no obvious means to differentiate areas of stable ice and unstable ice within the ship track; (2) Rough ice can be identified through satellite analysis to a degree (Figure 4), but some areas interpreted as rough ice were shown to be smooth ice; (3) Polynyas are identifiable on Standard imagery, but are very similar in tone and pattern to smooth ice and therefore ground-truthing is necessary.

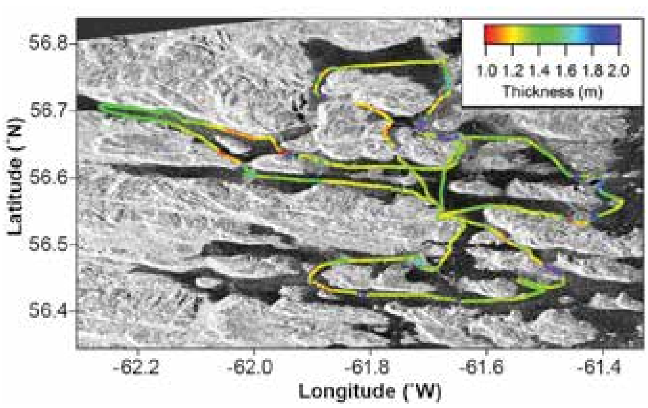

Figure 3. Ice thickness map generated by the prototype ice-sled mounted SmartQAMUTIK ice-thickness sensor in the Nain region.

CAM (Cost-of-Adaptation Mapping)

The initial work on this component has been focused in Arviat, the third largest Nunavut community, located on the western shore of Hudson Bay (Figure 2). As in many other northern locations, population growth is exacerbating a housing shortage that is leading to rapid development. Foundation instability has been identified as a cause of housing envelope damage, even in relatively new homes, suggesting the need to integrate new knowledge of ground conditions into the planning process, engineering design, construction protocols, and maintenance approach. A preliminary surficial geology map of the Arviat region is a first step in understanding local landscape hazards and thaw susceptible geological materials (Figure 5). The region

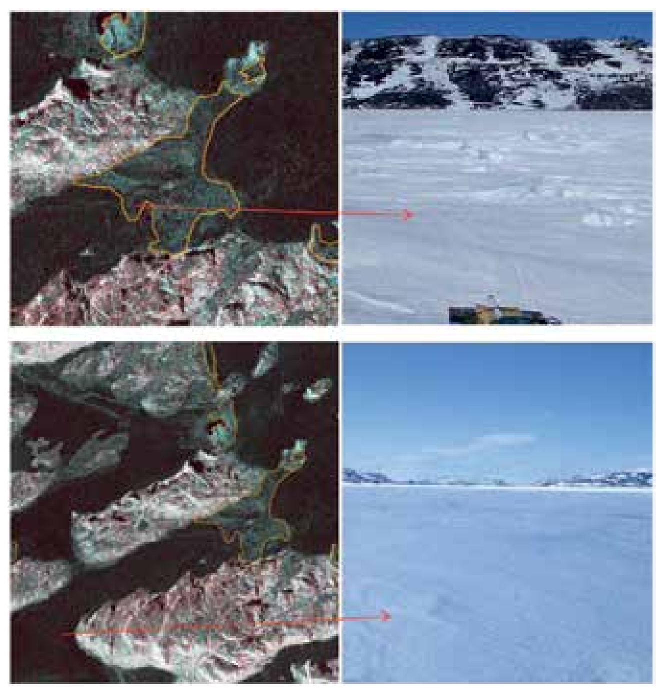

Figure 4. Rough ice (delineated in yellow) visible on the April 11th image (top left) is corroborated by ground truth observations on April 20th (still from video; top right). Smooth ice on the April 11th image (bottom left) is corroborated by ground truth on April 20th.

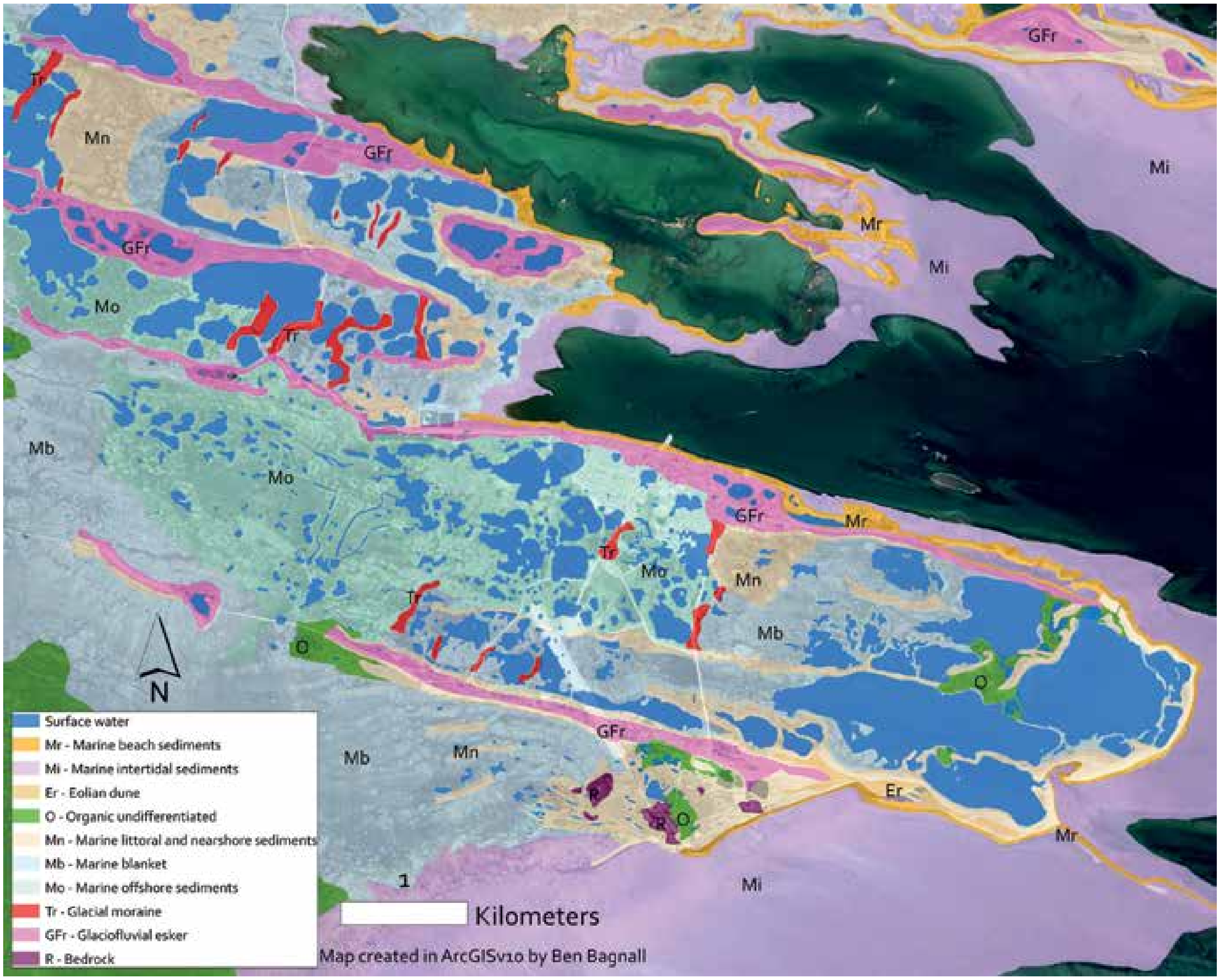

Figure 5. Preliminary surficial geology map of Arviat showing the dominance of glaciofluvial and marine sediments. The Arviat landscape is largely a product of continental ice sheet deglaciation and the legacy of recent emergence from the seafloor of Hudson Bay. Ponds that were mapped from aerial photographs predating the community expansion are shown on the map and appear superimposed on top of the current infrastructure (e.g. runway, housing divisions).

is dominated by deglacial landforms and sediments, in particular eskers and moraines, that have controlled landscape evolution during postglacial emergence. The overall flatness of the emerged coastal plain together with a network of esker and moraine ridges have restricted drainage and created a mosaic of shallow ponds and wetlands that experience fluctuating water levels over the summer and fall.

Drainage, especially during the snowmelt season, is a key landscape hazard that requires constant attention and influences community planning (Figure 6). The hamlet was initially established on the northern esker ridge but rapid growth has seen new housing and community infrastructure expand to the south and into the poorly drained lowlands. As a result, the hamlet has had to fill in shallow ponds to create building lots and the new runway (Figure 5). Our project is evaluating the

Figure 6. Poor drainage around housing is a health concern and potential cause of differential thaw subsidence and foundation instability in Arviat.

impacts of these in-filled ponds on terrain stability and infrastructure maintenance.

Another focus of the project is the delineation of thaw-sensitive permafrost terrain and surficial sediments that are challenging to build on. In the case of the former, rapid ground warming may result in differential ground subsidence and damage to buildings, roads and airstrips. This is a particular concern for Arviat where bedrock is deep below the surface and pile foundations have proven problematic. A particularly challenging surficial sediment in Arviat is locally called aimayumaima and sometimes referred to as quicksand (Figure 7 top). It is predominantly sandy silt or silty sand and outcrops in local pits and river-cut banks. When saturated, the aimayumaima may lose its bearing capacity, which has proven problematic in the past (Figure 7 bottom).

The decision-mapping component of the project is attempting to understand how housing development decisions are made and implemented in Arviat, which identifies where and when (entry points) geotechnical information can have the greatest benefit. For example, how are building lots selected and prepared? How are gravel pads designed and constructed? How are foundation types selected? What kinds of information are taken into account when making decisions? How is local knowledge incorporated into housing decisions? We are currently analyzing the results of our semi-structured interviews with key informants (experts or decision makers) on housing decisions in Arviat.

Figure 7. (top) Thixotropic sandy silt or silty sand, known locally as aimayumaima, is unsatisfactory as foundation material – surficial sediment mapping is important to determine the origin and distribution of this unit. (bottom) Loading thixotropic sediment with equipment or a building can result in a loss of bearing capacity.

CARRA (Coastal Archaeological Resources Risk Assessment)

Canada's coastal archaeology is at risk to the impacts of rising sea level. For example, in Newfoundland and Labrador, where 80% of all known archaeological sites are within a coastal context, our analysis of four key cultural regions indicates that roughly one-third of

Figure 8. Inuvialuit cabin at Nunaluk Spit, Ivvavik National Park, Yukon coast in 2012; as of 2015 the cabin is undercut but the bluff slope.

sites are currently eroding and in less than a decade this number is projected to increase to 40% or more. Along the Beaufort Sea coast, in the Inuvialuit Settlement Region, sites surveyed in the 1990s have completely disappeared and others are at the point of being lost (Figure 8), while traditional knowledge recognizes many places where former habitations are now beneath the sea (Lamoureux et al. 2015). Given the high proportion of archaeological sites at risk, there is a need to prioritize which sites should receive immediate attention. Our review of the scant literature on prioritization of archaeological resources suggests the following seven factors should be part of any evaluation process: Current Condition, Future Vulnerability, Rarity, Recreation/Tourism Value, Historical Significance, Scientific Significance, and Public Significance.

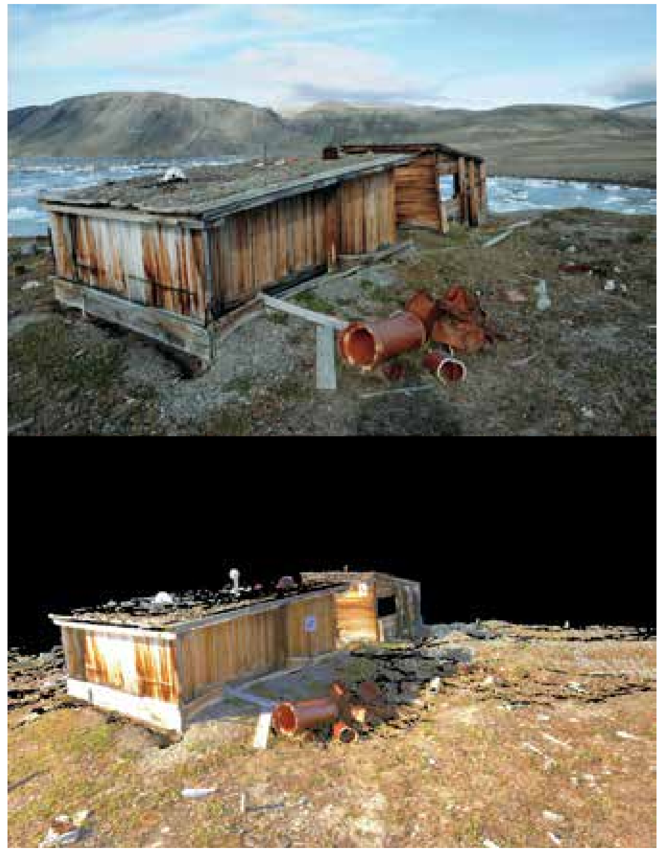

Figure 9. (top) Peary huts at Fort Conger as they appeared in 2010. (bottom) Image of the registered TLS point clouds of the Peary huts and associated artefacts. Both images are from Dawson et al. (2013). © 2013 Arctic Institute of North America of the University of Calgary.

Of particular interest is the potential application of Terrestrial Laser Scanning (TLS) at Fort Conger in Quttinirpaaq National Park, Ellesmere Island (Figure 9 top). The site is under threat from direct and indirect impacts of climate change, which include increased rates of biodegradation and deterioration, coastal erosion, the movement/removal of artefacts and inorganic contamination (Bertulli et al. 2013; Dawson et al. 2015). Although monitoring protocols have been established to evaluate these impacts, including repeat photography and coastal surveys, TLS represents a new technology that can be used effectively to document important cultural heritage sites in remote areas of the Canadian Arctic. The 3-D scanning data (Figure 9 bottom) can be used as a baseline to manage the future impacts of natural processes and human activities, while conservation and restoration work can be planned from the resulting 3-D models (Dawson et al. 2013).

Coastal flooding and erosion hazards

Flooding in the Mackenzie Delta (Figure 10), the largest delta in Canada and second largest on the Arctic Ocean, is dominated by spring snowmelt discharge and associated ice breakup. This annual event represents

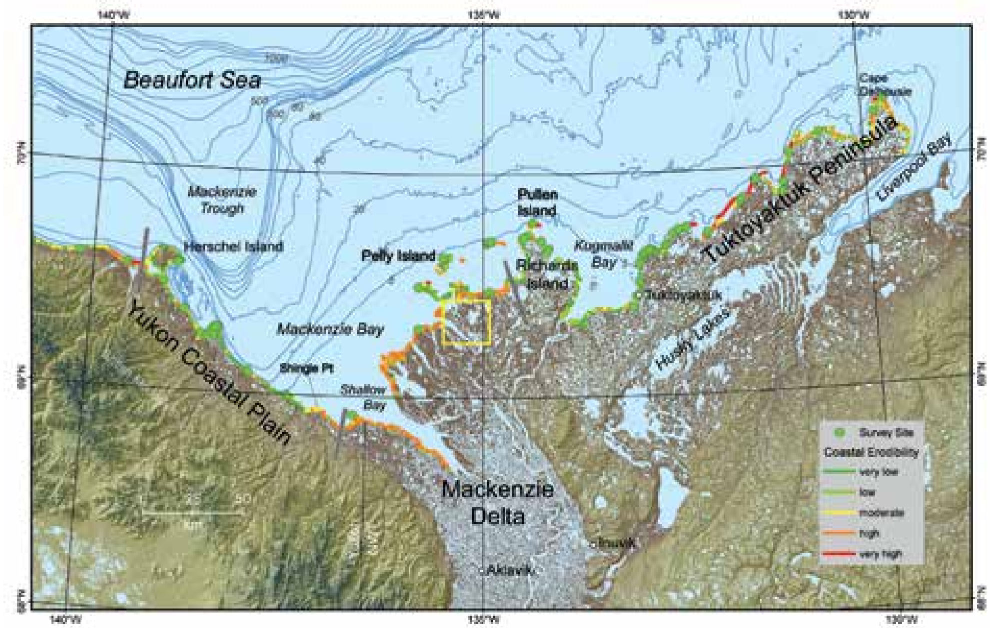

Figure 10. Canadian Beaufort Sea coast showing northern two-thirds of Mackenzie Delta, Yukon coast, and the Tuktoyaktuk Peninsula; also shows the communities of Aklavik, Inuvik, and Tuktoyaktuk , the subsistence community of Shingle Point, and Pelly and Pullen islands north of the delta. Colours represent a CanCoast erodibility index and green dots are Geological Survey of Canada coastal survey sites. Yellow box shows approximate extent of DEM in the delta shown in Figure 11.

a major hazard to delta residents and infrastructure, including the communities of Aklavik and Inuvik and subsistence camps throughout the delta. It is a time when supply lines are cut off as the winter ice roads disintegrate and broken ice or ice jams preclude water transport. From an ecological perspective, the spring peak flood level determines the distribution of nutrients to the 43,000 lakes in the delta (Emmerton et al. 2007, Crasto et al. 2015) and the extent of overbank flooding to supply sediment for upward growth of the delta plain to counteract rising sea level and delta subsidence (Forbes et al. 2015c).

The Mackenzie-Beaufort Breakup Newsletter has been a medium for sharing situational information on the status of breakup (ice cover and condition, flood levels and timing, and the gradual reopening of delta waterways) among residents, community decision-makers, emergency responders, government, industry, and the research community for several years. It is one model for knowledge mobilization at a regional (multi-community) scale and appears to be highly valued by the 300+ recipients and local contributors. We are currently re-evaluating the e-mail model with the aim of going to a more interactive approach rooted in the community (Forbes et al. 2015d).

Measurements of delta plain subsidence (the first in a large permafrost delta) and sedimentation rates suggest that the outer delta is not maintaining pace with rising relative sea level. Simulations using LiDAR digital elevation data with a realistic sea-level projection (median of RCP8.5 at Tuktoyaktuk, from James et al. 2014, 2015), measured subsidence (representative value of 4.2 mm/a), and a generous estimate of sedimentation rate (5 mm/a) project the permanent inundation of an additional 18% of the area shown in Figure 11a (26% of the land area today) by 2085 (Figure 11b). Spring flooding and storm surges today can cover most of the delta plain temporarily. The inundation shown here represents true habitat loss (Forbes et al. 2015c).

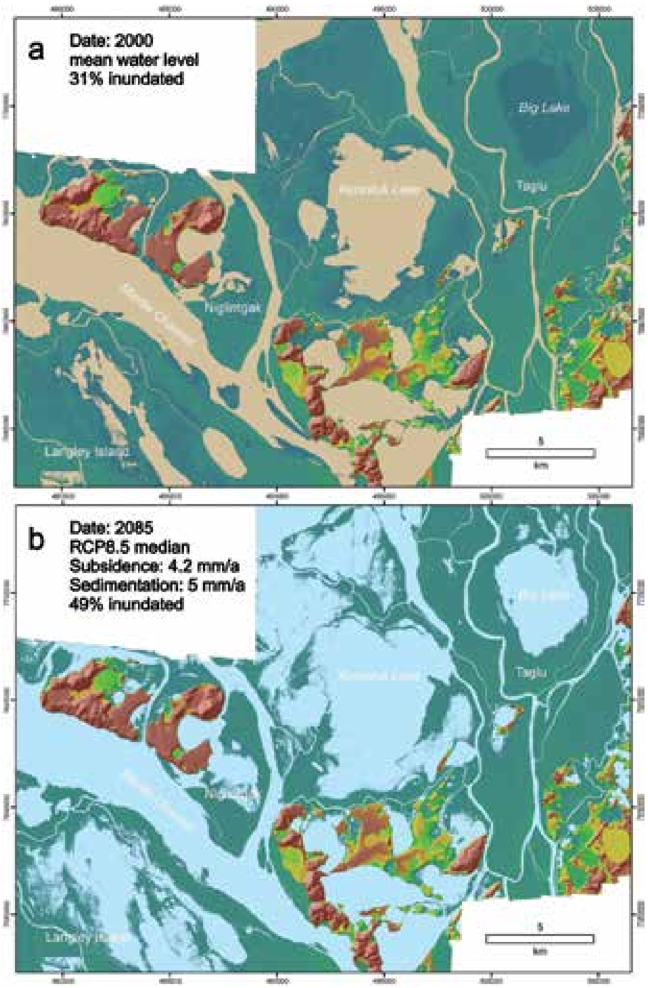

Figure 11. LiDAR digital elevation model for an area of about 600 km² in the outer Mackenzie Delta (yellow box in Fig. 10), showing onlap of the Holocene delta over older, deeply frozen, Pleistocene deposits (showing up in browns and yellows protruding through the delta plain). Upper panel (a): Turbid water at mean water level in the year 2000 covers 31% of the area. Lower panel (b): Assuming the realistic scenario shown in the legend, 49% of the area will be covered at mean water level in 2085.

New survey and time-lapse photo work by Whalen along the Beaufort Sea coast revealed distinct differences in erosion mechanisms and associated spatial variability in erosion rates on islands off the Mackenzie Delta. Erosion of Pelly Island, dominated by large block failures, has forced repeated relocation over many years of a critical meteorological station. Despite a lack of

Figure 12. Cliff face at Tuktoyaktuk Island following a storm surge in August 2002. Note deep undercut niche in massive ice at the base of the cliff. This will lead to collapse of large blocks defined by dimensions of ice-wedge polygons. Photo by our late colleague Steve Solomon.

storm surge activity in the summer of 2015, almost 40 m of erosion occurred between June and August.

Erosion of Tuktoyaktuk Island (Figure 12) has removed more than half the width of the island in recent decades and the remaining island may be susceptible to more rapid loss. As the island provides natural protection for the port, its gradual reduction has been a growing concern to residents and industry reliant on the harbour and to territorial and federal policy makers (GNWT, Transport Canada) concerned with northern marine transport reliability. The island is entirely Inuvialuit land and therefore the responsibility of the Inuvialuit Land Administration, which is looking to this project for scientific advice in its consideration of viable protection measures (Whalen et al. 2015).

Work on sea-level projections and coastal hazards in the City of Iqaluit supported development of the current sustainability plan and a new synthesis of results dispelling some concerns and identifying specific risks was published in December (Hatcher and Forbes 2015). This demonstrated that some waterfront infrastructure is currently at risk of flooding (notably informal infrastructure supporting access to

Figure 13. Freeze-up along the waterfront at Iqaluit, November 2011, showing high-tide flooding to the doorsteps of subsistence infrastructure, freezing to form incipient icefoot; even slight changes in sea level, storm climate or ice dynamics could put these buildings at risk, but urban development behind them limits options for setback. Source: Hatcher and Forbes 2015. © 2015 Arctic Institute of North America of the University of Calgary. © Her Majesty the Queen in Right of Canada.

country food) and some critical infrastructure such as the sewage berms may be at risk of overtopping under the upper-limit projections of sea-level rise. The subsistence infrastructure is already experiencing coastal squeeze, with other development precluding setback options (Figure 13). This represents both an environmental and an equity challenge for sustainable development. With the increasing length of the open-water season, the Iqaluit waterfront and potential port development site may be subject to increasing wave impacts, although the fetch is limited to 50 km by the band of islands protecting inner Frobisher Bay. Significant wave attenuation occurs across the tidal flats in front of the urban core, except at the highest tides, which is when any overtopping occurs. This work also provided some of the first documentation of freeze-up, when some onshore ice impacts can occur, before full development of the icefoot (Figure 13).

Coastal Weather Hazards

This component of the project focuses on local-scale weather effects along the western Arctic coast and addresses issues relevant to communities, industry (including marine and river shipping), and operational and emergency response groups (Atkinson et al. 2014, Eerkes-Medrano et al. 2015). Consultation with one industrial operator (NTCL) revealed poor visibility is the dominant cause of lost shipping days, as many as 20 in a 100-day shipping season. Coastal weather is now more variable than in the past. Traditional knowledge is being challenged by changing norms and our premise is that it can be supplemented by operational weather forecasting if local-scale 'problematic' weather events can be linked to larger-scale weather patterns to improve the utility of forecasts for northern residents and ultimately improve safety. The project has also acquired data to help fill knowledge gaps at the community level. A key facilitator of this work has been the attention to local priorities in the design and implementation of the research, through identification of local research champions, maintaining open lines of communication on an ongoing basis between face-to-face meetings, and ensuring local access to co-produced knowledge. The new results on coastal wave energy and swell occurrence are directly applicable to sea-lift operations and marine transport infrastructure (harbours and offloading facilities). These activities are supported by PhD students Norman Shippee and Laura Eerkes-Medrano.

DISCUSSION

CACCON

The Circumpolar Arctic Coastal Communities Observatory Network (CACCON) ['*Catch-On*'] is a pan-Arctic network of community-engaged, multi-faceted, and integrative coastal observatories and knowledge hubs. It addresses a gap identified in the *State of the Arctic Coast 2010* report (Forbes 2011). The CACCON observatories facilitate co-design of research agendas and co-production of knowledge with local and regional stakeholders, building capacity through sharing insights between stakeholder peers across the circumpolar world to identify information needs and effective adaptation measures. The starting point for the network is the existing web of coastal observational datasets as well as existing community-based monitoring programs and compilations of traditional knowledge. Through a collaborative process involving end users, information available from these existing sources is being compiled and assessed to extract a set of indicators that will be relevant for local, regional, and larger-scale decision-making. These indicators will then define a core set of future community-based observations, providing a basis for policy development and planning, to be supplemented by efforts supporting locally-identified priority issues. The acceptability and utility of any set of indicators depend on ownership by the community and fitness for purpose. This points to the need for co-design by and with users and choice of indicators appropriate to scale and tailored to the circumstances of the particular communities, regions, or networks involved. There is as yet little experience in the development or application of effective sustainability indices in Arctic communities, but we can draw on initial experience with adaptive capacity indicators (Alessa et al. 2016). Any number of indicators may be developed in response to specific issues in individual communities or regions, addressing local priorities. The goal is to select robust indicators that will be useful to decision-makers at the community or household scale and can be co-produced by and for the community. Is there a small set of common resilience or sustainability indices that can be developed and applied across regions and at a circumpolar scale in CACCON? The project will be addressing this question with network partners and other initiatives over the coming year.

Despite the need for an enhanced research focus on addressing the pressing challenges of environmental and social change in northern communities, there remains a major gap in the level of effort directed to northern sustainability needs (Rosen 2016). Substantial progress has been made in this first year of the project, growing or initiating solutions-oriented activities in at least seven northern communities (Figure 2). SmartICE addresses a community priorities for timely sea-ice information to support safe travel in Nain and Pond Inlet. It is augmenting local sea-ice knowledge (not replacing it), while building local capacity in a number of ways, in particular through northern peer interactions from one community to another. SmartICE was first developed in Nunatsiavut communities and is now expanding to Nunavut, with Labrador Inuit working alongside and training Inuit from Pond Inlet. And although primarily designed to support ice-travel safety in northern communities, SmartICE observations can inform winter fishery and harvesting programs, search-and-rescue operations, climate-change adaptation planning, ecosystem monitoring, and sea-ice technology validation.

The Cost-of-Adaptation Mapping (CAM) project responds to the information needs of northern communities by revealing the costs and benefits of adaptation choices in the selection and preparation of building sites and the design and construction of community infrastructure. It is augmenting local knowledge and expertise while strengthening capacity to make effective place-based, climate-adapted, infrastructure choices. The CAM project is being piloted in Arviat (NU) and Old Crow (YK). It builds on the hazard and vulnerability mapping in these communities by using their map products as the basis to show how adaptation actions can make more community land available for infrastructure development.

Decision-tree mapping is revealing the processes by which decisions on building land development, lot preparation and foundation selection are being made and implemented in Arviat. It identifies the entry points through which geoscience knowledge can have the greatest benefit for the development of sustainable infrastructure in Arviat and other Nunavut communities.

Canada's coastal archaeology is at risk to the impacts of rising sea level. The *Coastal Archaeological Resources Risk Assessment* (CARRA) project addresses the needs of heritage managers for tools and best practices to respond to an ever-increasing number of at-risk sites in coastal Canada.

The CanCoast data are informing understanding of spatially variable climate-change impacts on Canadian Arctic coasts and provide a framework for more detailed regional hazard assessment (e.g. Figure 10) and local-scale coastal mapping (e.g. Hatcher and Forbes 2015). They have also attracted other users, including Fisheries and Oceans Canada for standardized mapping of species at risk, and Transport Canada to overlay transport infrastructure data to aid in assessing vulnerability. Within this project, coastal flooding and erosion hazards have been addressed in the Mackenzie Delta and Beaufort Sea, contributing to issues of primary concern to regional, territorial, and federal agencies and local residents: flood frequency and inundation, threats to marine and terrestrial habitat, risk to cultural resources and subsistence infrastructure, and long-term viability of the port of Tuktoyaktuk. Similar work in Arviat, Hall Beach, and Iqaluit aims to identify and quantify coastal hazards relevant to community concerns.

CONCLUSION

Next steps in the project focus particularly on the CACCON challenge of knowledge acquisition and mobilization to meet community needs. We aim to facilitate meetings among CACCON communities, both face-to-face and experimenting with northern virtual infrastructure options. A prime objective is encouragement of community-to-community knowledge transfer, as exemplified in the SmartICE collaboration between Nain and Pond Inlet, and anticipated in the CAM connection between Arviat and Old Crow. Promoting solutions-oriented research in the Arctic coastal zone, the project has successfully launched these initiatives as CACCON proof-of-concept and we anticipate deepening engagement within the network and with our numerous partner initiatives over the coming year.

ACKNOWLEDGEMENTS

This project benefits from the efforts and engagement of a long list of northern residents, community research champions, academic and government partners, international colleagues, and governance institutions at municipal, regional, territorial, and federal levels. We are particularly indebted to past and present ArcticNet students who have contributed to this and preceding projects. It is a pleasure to acknowledge the financial support of ArcticNet and NCE Canada to enable this work to go forward. Financial and in-kind support has also come from numerous other institutions and agencies, which are acknowledged specifically in the reports and papers arising from the project.

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Enhancing Community-Based Environmental Monitoring in the Canadian Arctic for Local and Regional Assessments and Adaptation Strategies

Project Leader

Greg Henry (University of British Columbia)

Network Investigators

Alain Cuerrier (Université de Montréal)
Luise Hermanutz (Memorial University of Newfoundland)
Trevor Lantz (University of Victoria)
Esther Lévesque (Université du Québec à Trois-Rivières)

Collaborators

Monique Bernier (Institut national de la recherche scientifique - Eau, Terre et Environnement)
Anne Bjorkman (University of Edinburgh)
Stéphane Boudreau (Université Laval)
Karin Clark (Government of the Northwest Territories)
Daniel Fortier (Université de Montréal)
Robert Fraser (Natural Resources Canada - Geomatics Canada)
Gilles Gauthier (Université Laval)
Paul Grogan (Queen's University)
Steven Kokelj (Aboriginal Affairs and Northern Development Canada)
Daniel Lafleur (Kativik School Board)
Scott Lamoureux (Queen's University)
Isla Myers-Smith (--)
Susan Nelson (Kativik School Board)
Neal Scott (Queen's University)
Warwick Vincent (Université Laval)

HQP

Noémie Boulanger-Lapointe, Doctoral Student (University of British Columbia)
Placing berries in the Arctic food chain: Plant productivity and bio-cultural value in the Canadian Arctic / Identifier la place des espèces productrices de petits fruits dans la chaine alimentaire arctique: productivité végétale et valeur bio-culturelle
Vanessa Mardones, Doctoral Student (Memorial University of Newfoundland)
The ethnobotany and medicinal properties of Rhodiola rosea in Nunatsiavut and potential applications in community-based nutraceutical marketing enterprises
Michel Rapinski, Doctoral Student (Institut de recherche en biologie végétale)
Guillaume Rheault, Doctoral Student (Université du Québec à Trois-Rivières)
Laura Siegwart Collier, Doctoral Student (Memorial University of Newfoundland)
Émilie Hébert-Houle, Masters Student (Université du Québec à Trois-Rivières)
Marc-André Lemay, Masters Student (Université Laval)
Isabelle Lussier, Masters Student (Université du Québec à Trois-Rivières)
Katriina O'Kane, Masters Student (University of British Columbia)
Marilie Trudel, Masters Student (Université du Québec à Trois-Rivières)
Esther Frei, Post-Doctoral Fellow (University of British Columbia)
Emily Cameron, Research Associate (University of Victoria)

Yves Gauthier, Research Associate (Institut national de la recherche scientifique - Eau, Terre et Environnement)
José Gérin-Lajoie, Research Associate (Centre d'études nordiques)
Kazlyn Bonnor, Technical Staff (University of Victoria)
Ariane Bisson, Undergraduate Student (Université du Québec à Trois-Rivières)
Danielle Black, Undergraduate Student (University of British Columbia)
Jason Dicker, Undergraduate Student (Kangidluasuk)
Cassandra Elphinstone, Undergraduate Student (University of British Columbia)
Amélie Lapointe, Undergraduate Student (Université du Québec à Trois-Rivières)
Mélanie Normandeau-Bonneau, Undergraduate Student (Université du Québec à Trois-Rivières)

Northern HQP

MacCombie Annanack, Northern Research Staff (Community of George River)
Rhoda Kayakjuak, Northern Research Staff (Uqausiit Communication Services)
Lucassie Tooktoo, Northern Research Staff (Umiujaq)

ABSTRACT

The Arctic is experiencing rapid environmental change, and communities are seeing and feeling the changes directly. Climate warming is resulting in thawing permafrost and unstable land, affecting community and industrial infrastructure. The warming is also increasing the growth of shrubs and changing the vegetation, which in turn will affect smaller plant species, such as berry plants and lichens, and affect important wildlife species, such as caribou. In addition, landscape disturbances, such as thaw slumps and fires, are becoming more frequent and larger, affecting travel routes and the land and water systems. Besides these natural disturbances, industrial impacts are increasing as the pace of development accelerates in many areas of the Canadian Arctic. In order to better cope with and adapt to the changes in their environment, Inuit and other northerners need a wide range of information that is relevant to their local and regional circumstances. Scientific research and monitoring provide important sources of information for understanding the impacts and consequences of the environmental changes. However, land users in communities across the Arctic have the unique perspectives of being on the land, noting the changes in the context of their sophisticated understanding of their environment. In our project, we will conduct studies to bring together both scientific and community-based monitoring of the environmental changes that is relevant to communities. We will use a combination of interviews, mapping, remote sensing and plot level studies to provide the diverse information needed to understand and adapt to the changing environment. We will introduce a new web-based interactive mapping platform (the Community Knowledge Keeper) to help communities catalogue and store traditional knowledge and indigenous information on environmental change. We will also work with high school science classes in each of the communities to train students in measurement techniques for environmental monitoring. They will also learn to interview elders to gain Inuit perspectives on how the environment is changing and how to adapt. We will also continue to collaborate with Nunavut Arctic College Environmental Technology Program in Iqaluit, by introducing new monitoring protocols and participatory multimedia mapping. Ultimately, we hope to see a network of sustained community-based environmental monitoring across the Canadian Arctic that contributes needed information for communities, scientists and governments.

KEY MESSAGES

- The productivity of berry shrubs is not strongly correlated with weather patterns across the Canadian Arctic. Other local factors, such as presence of erect shrubs and soil conditions are important in determining productivity.
- Berry productivity is lower under erect shrub cover, especially for blueberry (*Vaccinium uliginosum*) and blackberry (*Empetrum nigrum*).
- Hence, berry productivity will likely decrease with increasing erect shrub cover, which is predicted as a response to the warming Arctic climate.
- Blackberry use by snow geese and harvesting by people in near Arviat was found to be about 2% of the total production in the region. At least in this area, use of berries by wildlife and people is not affecting production.
- Arctic landscapes that are rich in ground ice are highly sensitive because climate change can catalyze disturbances with significant ecological and geomorphological impacts. Recent mapping indicates that the ice-rich deposits on Banks Island have the highest density of permafrost disturbances in the Canadian Arctic.
- The changes across the Canadian Arctic in recent years are variable, as described in interviews conducted by our team in communities across Nunatsiavut, Nunavik and Nunavut over the course of our ArcticNet projects. A book based on the interviews will be released in March 2016.

- Science education is a key to building capacity in the Arctic among residents. The *Avativut* program now has all three modules (berry productivity, ice monitoring, and permafrost dynamics) implemented with secondary schools in the Kativik School Board science curriculum.
- *Rhodiola rosea* (Roseroot) in Nunatsiavut contains all known bioactive constituents of commercially traded (Eurasian) *Rhodiola*, but due to its ecological breadth, Nunatsiavut *Rhodiola* exhibits variability in growth and phytochemistry.
- The market for natural health products shows consistent growth, and Nunatsiavut *Rhodiola* could occupy a unique market niche. Nunatsiavut Inuit community members have unique knowledge of and traditional uses for the local *Rhodiola*, and they are supportive, and cautiously optimistic about applying traditional knowledge towards a community-based enterprise.

OBJECTIVES

The overarching objective of our research is to enhance local environmental monitoring across the Canadian Arctic such that the programs are self-sustaining and become important sources of information for local and regional assessments of change and facilitate the development of policy for adaptation and resilience. We build on our successful community-based research focussed on berry production and vegetation change in Nunavut, Nunavik and Nunatsiavut, and expanded the research into the Inuvialuit Settlement Region (ISR). Ultimately, we wish to facilitate the long-term stewardship of this knowledge base in each region and provide a lasting legacy of ArcticNet.

The project has three general objectives for research with and near communities:

1. Enhance existing community-based berry production and vegetation monitoring in Canadian Arctic communities.
2. Conduct environmental monitoring of importance to communities.
3. Strengthen involvement of Inuit youth in environmental monitoring using science and Inuit knowledge.

INTRODUCTION

Rising air temperatures and increasing disturbance (natural and human-caused) are driving rapid ecological change across the Canadian Arctic (ACIA 2005; Henry et al. 2012; IPCC 2014). Recent changes include shifts in the frequency and magnitude of natural disturbances, changes in the timing of formation and melt of sea and lake ice, permafrost degradation and decreasing land stability, changes to vegetation structure, shifts in animal population size and distribution, and changing water quality and quantity (e.g. Elmendorf et al. 2012; Kokelj et al. 2013; Lantz et al. 2009; Sturm et al. 2005). These environmental changes have impacts at local and regional scales, including potential positive feedbacks to climate warming through vegetation change and altered energy and carbon flux (Chapin et al. 2005; Elberling et al. 2013). They also impact northern indigenous communities whose livelihoods and well-being are linked to the health of the land (Krupnik and Jolly 2002; Parlee et al. 2005). Impacts can be direct (e.g. loss of travel route) or indirect (e.g. changes in vegetation and cascading effects on culturally important foods, such as berries). In order for northern communities, researchers, and decision makers to manage and adapt to changing environmental conditions, diverse information about the location, extent, and drivers of local and regional changes is needed (Pearce et al. 2009). Many Inuvialuit and Inuit land users are in a unique position to monitor local environmental conditions and detect changes because they spend a large portion of the year on the land and have a sophisticated understanding of historical environmental variation. The number of research programs in the Canadian Arctic that have incorporated Inuit and Inuvialuit knowledge (IK) has grown considerably over the past 20 years, and IK was an essential component International Polar Year program (Grimwod et al. 2012; Henry et al. 2012; Kulkarni et al. 2012). However, despite ongoing interest in environmental research that integrates local knowledge, significant challenges remain in implementing programs consistent with community needs that will provide the long-term data sets required by environmental scientists, regional planners and regulators (Bonny and Berkes 2008; Brunet et al. 2014). Our ArcticNet project aims to enhance the integration of environmental research and monitoring with local knowledge and to provide a lasting legacy for communities to build on.

ACTIVITIES

Fieldwork was conducted across the Arctic throughout the summer 2015 and included measurements of berry production and vegetation change near communities and at long-term research sites. Community based monitoring continued in all regions of the Canadian Arctic, with new research started in Sachs Harbour in the Inuvialuit Settlement Region.

Tundra plant ecology, berry productivity and environmental change

- Impact of shrubification (increased height and density of erect shrubs) on berry productivity was studied in Umiujaq, Nunavik, and Nain and Torngat Mountains National Park (TMNP) in Nunatsiavut.
- At Umiujaq vegetation and berry productivity was measured in ten plots (30 m x 30 m) that span a gradient of shrub densities and berry productivity. Environmental variables, including soil characteristics were also measured.
- Berry production and use by animals and people was assessed at Arviat in permanent plots and mapped using plot data and satellite imagery.
- Measurements of berry production and vegetation change were conducted on Bylot Island, Nunavut in long-term experimental plots (13 seasons). Species abundance and composition was measured in 72 permanent plots using the standardized point-frame method established for the International Tundra Experiment (ITEX). The influence of grazing by geese on vegetation was assessed in exclosure plots, where the geese have been excluded since 2002.
- Measurements of berry production and species composition and abundance were completed in 78 long-term plots at the Alexandra Fiord research site on Ellesmere Island, including a photographic method developed for the site (Beamish 2013; Chen et al. 2010). Phenology, growth and reproduction were also measured on focal species in permanent experimental climate change plots established in seven tundra plant communities and in common garden experiments (total of 213 plots).
- Effects of experimental warming using open top chambers on tundra vegetation was measured in TMNP, Bylot Island and Alexandra Fiord. At each site, species composition and abundance was measured using the ITEX point frame method.
- Berry production was measured in permanent plots the Daring Lake field station, NWT.
- A new study of the phenology of tundra wetlands was started at Umiujaq. The project involves the use of time-lapse photography to measure daily changes in flowering and greenness, and is part of a network of wetlands sites throughout Quebec.

Community-based environmental monitoring

- In Nunavik, all schools in the communities had the Learning and Evaluation Situation “How many berries are there?”, and students participated in measuring berry production using our protocols.

- In Nunavut, berry production was assessed in permanent plots at Pond Inlet, Arviat and Baker Lake with the help of students.
- Berry plots were harvested in Nain by our partners in the Nunatsiavut government and processed for the long-term pan-Canadian productivity study.
- Youth involved with the Arviat Climate Change project conducted field measurements of berry productivity and weekly monitoring of plant phenology in permanent plots.
- The youth in the Arviat project were trained to conducted interviews with their elders on land use and plants in Inuktitut and are currently involved in the translations to English.
- The teachers and students from the Environmental Technology Program, at Nunavut Arctic College, measured berry productivity, soil surface temperature, and plant cover in their permanent plots and four warming experiment plots (using open top chambers (OTCs)) at Peterhead Inlet, near Iqaluit, for the seventh year.
- In the summer of 2015, we worked with the Sachs Harbour HTC to identify and establish community monitoring sites near town. Five monitoring sites were established across the dominant terrain units (mineral polygon, peat polygon, sedge meadow, upland, and riparian). At these sites we collected vegetation data vegetation structure, community composition, soil moisture, soil pH, active layer thickness, ground temperature data at 10 cm and 1 m below the ground surface, as well as air temperature data. An additional ground temperature sensor was installed under an NWT Environment and Natural Resources building in Sachs Harbour. Ground and air temperature will be logged every 2 hours for the duration of the year.
- We conducted a pilot study in high-centered polygonal terrain exploring the factors associated with ice wedge degradation in an area near Sachs Harbour.

Education and Outreach

- The Permafrost LES (Learning and Evaluation Situation) was completed (linked to another ArcticNet project), which includes PermaSim, an interactive application for students to learn about permafrost processes. This completes the three modules of the Avativut Program, (berry productivity, ice monitoring and permafrost dynamics) and they are now implemented as LES in the Kativik School Board Science curriculum for first and second cycles in secondary schools.
- Data collected by the schools for the berry productivity are being compiled and will be analyzed, and results in the form of graphics will be produced for the schools to increase engagement with the students.
- The Avativut Mobile Teacher Training Workshop was held in two Nunavik communities: Salluit and Kangiqsujuaq during November 2015.
- Links were developed with the Environmental Technology Program of Arctic College in Iqaluit. A presentation by J. Gérin-Lajoie outlined the Avativut program in Nunavik and the protocols used. She also presented the berry production data from plots near Iqaluit monitored by ETP students over the past seven years.
- Posters based on local knowledge of plants and berry production that has been collected since 2008 were presented in Baker Lake and Pond Inlet, Nunavut.
- A book describing the observations of elders in Kugluktuk of changes in berry production, as well as stories about and recipes involving berries is set to be published in June 2016. The book is in Innuaqtun and English.
- The book based on our interviews with elders and other knowledge holders in eight communities across Nunavut, Nunavik and Nunatsiavut during 2007-2010 (*The Caribou Taste Different Now Inuit Observations of Climate Change*) was completed and will be published and released by Arctic College in March 2016.

- A documentary film *Nallua* shot in and around Pond Inlet, Nunavut, was released in June 2015 at the “Festival Présence autochtone/Montreal First Peoples Festival” in Montreal. The film was an independent artistic project stemming from a community request, which was linked to the work by Esther Lévesque and José Gérin-Lajoie in our ArcticNet research project in the community.

Natural health products: Rhodiola rosea

- Harvest and preliminary cultivation of *Rhodiola rosea* (Roseroot) from areas near Rigolet, Nunatsiavut, continued in 2015.
- Interviews with Inuit elders and community members were held regarding concerns and opportunities for development of a community-based business using cultivated *Rhodiola*.
- A business opportunity analysis was conducted to determine potential for natural health products developed from *Rhodiola* in Labrador / Nunatsiavut. This will lead to the development of a full business plan.

Syntheses and Database Activities

- Syntheses of Inuit observations of changes in Canadian Arctic communities conducted over the past eight years were completed and submitted.
- Book manuscript of interviews with elders in eight Arctic communities was completed and translated into eastern Arctic Inuktitut and English, and is to be available in March 2016.
- Analysis of berry production in four species measured in all of our sites since 2008 is currently underway.
- Species composition and abundance data used in global synthesis of tundra plant community changes linked to ITEX.
- Phenology measurements from our sites used in global synthesis of phenology of tundra plants linked to ITEX.
- Preliminary discussions were held with Kwusen Research & Media (www.knowledgekeeper.ca) for the development of a web site for access and use of our project data by northern communities.
- We had discussions with Joel Heath, Arctic Eider Society, to use elements of his project on using a social media network and interactive knowledge mapping platform (IK-MAP), which was designed with and for northerners.

RESULTS

We had a very successful start to the new phase in our project, highlighted by new research in the Inuvialuit Settlement Region (ISR) in the NWT. With the studies initiated in the ISR, our research now spans all Inuit regions of Arctic Canada. Fieldwork continued in ten communities and four research sites, with a focus on the continued measurement of berry production in permanent plots by students in local school science classes. In some communities, these measurements have been conducted successfully since 2008 and the data are being used in a synthesis of berry productivity across the Canadian Arctic that will be completed in the next year. In addition, completed research by graduate students has provided greater insight into the controls of berry production and the impacts of climate change and shrubification. Tundra vegetation data from our communities and experimental sites, based on the standard point frame method developed for the International Tundra Experiment (Figure 1), are being used in global syntheses to determine patterns of responses to climate change across the tundra biome.

Our work with the schools in Nunavik has continued to be fruitful, with the completion of the last of the three Learning and Evaluation Situation (LES) modules that are used in all schools of the Kativik School Board in Nunavik. This was one of our original goals in the community-based monitoring project, established under the International Polar Year program and continued in ArcticNet. Including similar programs

Figure 1. Measuring species composition and abundance using the standardized point-frame method in permanent quadrats at Bylot Island, Nunavut. The plots were established to monitor plant abundance and diversity as part of a long term grazing experiment.

in schools across the Arctic will continued to be advocated by our group.

The use of Labrador populations of *Rhodiola rosea* as a natural health product continued to be pursued in Nunatsiavut and other Labrador communities. There is general support in the communities for developing a locally-controlled business using cultivated plants.

More detailed results from the past year are presented in the following sections.

Tundra plant ecology and berry productivity and environmental change

Tundra berry plants are affected by proximity to large erect shrubs, with berry shrub cover and productivity greater with distance from erect shrubs. At Umiujaq, the three berry shrub species (*Vaccinium uliginosum* (blueberry), *Vaccinium vitis-idaea* (cranberry or red berry) and *Empetrum nigrum* (blackberry)) were common in the landscape (found in 91% of quadrats), but were less frequent in areas near tall shrubs. Berry plant cover and berry production of all three species was significantly lower in plants under the cover of tall shrubs (Figure 2). In similar studies in Nunatsiavut, the total fruit production of the three berry species was significantly affected by the canopy cover or density of the taller shrubs (Figure 3). Blackberry production was better in drier soil conditions, while warmer soils were associated with greater fruit production in blueberry and cranberry (Figure 3). However, experimental warming reduced the production of blackberry in Nunatsiavut over three years, although the reduction was not significant.

Using satellite imagery and vegetation plots in different plant communities, berry production of the three major species was mapped in an land area of about 35 km^2 in the vicinity of Arviat, Nunavut. Total blackberry production in the area was estimated to be nearly 90,000 kg (Figure 4). Estimates of annual consumption of blackberries by snow geese (1,295 kg) and humans (785 kg) was only 2.3 % of the total production. Similar values were found for the other two berry species: blueberry and cranberry.

Community-based environmental monitoring

Results from the community-based monitoring of berry production are being analyzed in a synthesis of results from all permanent plots established in nine communities since 2008. The berry production results from each community are being compiled and graphics of the results will be produced and presented to the schools. Preliminary results shown in Henry et al. (2012) indicate the berry production is strongly controlled by local factors. The analysis of these data will be a first for the three major berry species used by communities across the Arctic.

Results from our interviews with elders and other knowledge holders in eight communities across the Arctic on how the environment was changing were analyzed using multivariate statistical methods (non-metric multidimensional scaling: NMDS) in order to determine patterns in the observations (Siegwart Collier et al. 2016 (in prep.)). We conducted 144 interviews from 2007 to 2010 (88 women and 56 men) and the answers to closed-ended questions

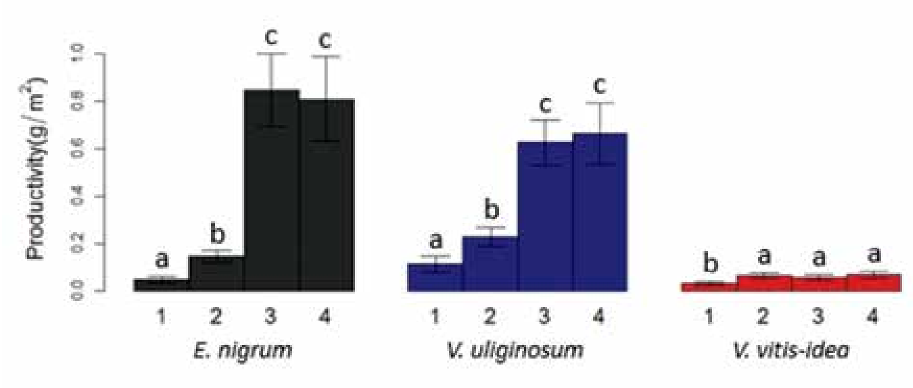

Figure 2. Productivity (dry fruit biomass in g/m²) of three berry plant species (Empetrum nigrum, Vaccinium uliginosum, V. vitis-idaea) in relation to position relative to tall shrub canopy: (1 = under shrub canopy; 2 = at the margin but in the canopy; 3 = at the margin but out of the canopy; 4 = in open habitat) (mean ± SE). Differences among treatments within each species were tested by Kruskal-Wallis analyses. Varying letters above bars show significant differences among means ($p < 0.05$).

were scored for the quantitative analysis shown in Figure 5. Common observations across communities included lesser amounts of snow and earlier sea ice melt. Our analyses indicated that there were significant differences in the observations of environmental change among the communities. For example, the western communities of Baker Lake and Kugluktuk reported less rain, while eastern communities (especially Nain and Kangiqsujuaq) report an increase in rainfall. There were also interesting variations in responses among participants in the same communities with common consensus regarding observations recorded in Pond Inlet and Kugluktuk, but a wider variety in some Nunavik communities.

Education and Outreach

The completion of the three LES modules for the Avativut program has solidified the use of environmental monitoring in the curriculum of the secondary science classes in Nunavik. The support provided by the teaching training in the modules was successful in two communities and will continue.

The book describing results of our interviews in eight communities across Nunatsiavut, Nunavik and Nunavut on Inuit observations of climate change (titled: "The Caribou Taste Different Now: Inuit Elders Observe Climate Change) (Figure 6) is to be released in March 2016. This will be a major contribution to the material available for education in northern Canada and elsewhere, and as a record of Inuit knowledge of environmental change.

Another book based on interviews and fieldwork conducted in Kugluktuk, Nunavut will have recipes, stories and information on changes in berry productivity. The interviews were conducted by students who were learning Innuaqtun, and they have contributed to the translations.

Although not directly related to our project, the documentary film *Nallua* was filmed in Pond Inlet and based on a local story, and was partly instigated by members of our project (E. Lévesque and J. Gérin-Lajoie) from conversations in Pond Inlet while conducting our community-based research. The film was released in June 2015, and has had critical acclaim across North America.

Natural health products: Rhodiola rosea

Nunatsiavut Inuit Elders and other community members report medicinal and food uses of *Rhodiola* (Roseroot) unique to Nunatsiavut, and shared distinctive traditional knowledge of its ecology.

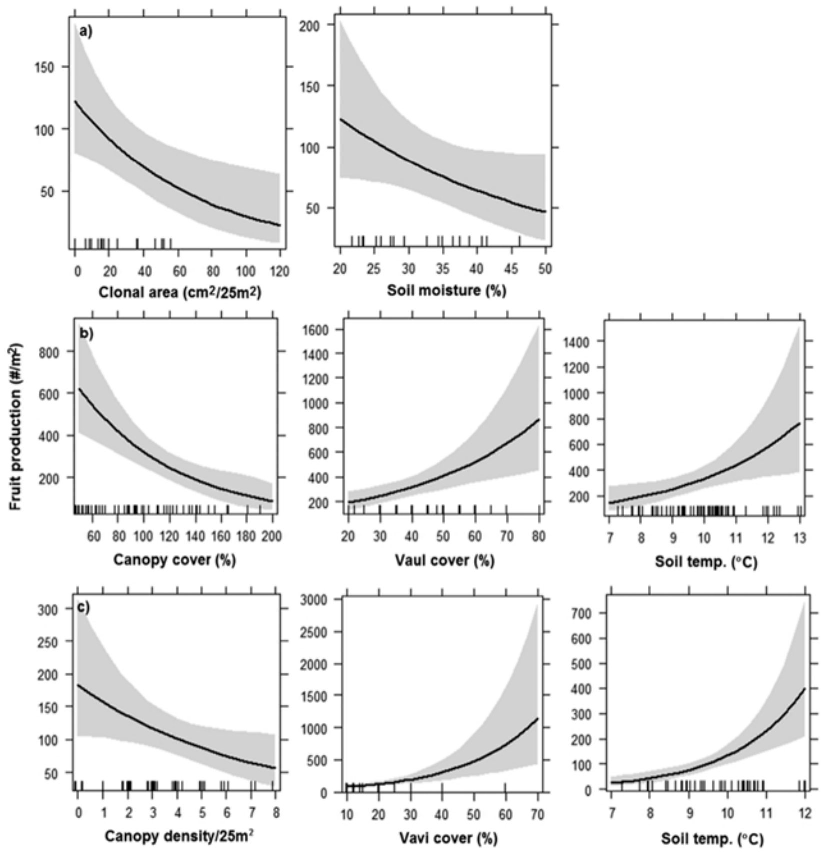

Figure 3. Effects plots from generalized linear regression (negative binomial error, log link) indicating the magnitude and strength of significant parameter effects on fruit production (total # fruits and flowers/m²) in a) Empetrum nigrum, b) Vaccinium uliginosum (Vaul) and c) Vaccinium vitis-idaea (Vavi). Shaded areas represent 95% confidence intervals.

Known locally to the Inuit as *tulligunnak*, Roseroot has been traditionally used to combat a wide variety of ailments, including melancholy and seasonal colds. Community members expressed concern for conservation of *Rhodiola* in the wild and how harvesting the local *Rhodiola* for propagation would affect the wild populations. However, they were enthusiastic about the potential benefits of an enterprise based on a local medicinal plant, while still maintaining a pragmatic outlook on possible economic outcomes. Benefits anticipated by community members were wide ranging, from the mental health benefits of spending time on the land, to increased pride in culture, as well as the economic benefits - employment and capacity building within the community. Currently, there are three pilot gardens cultivating Roseroot in the community of Rigolet, Nunatsiavut. These plants were harvested from the local coastlines due to rising water levels and storm surges such that the plants were in danger of being lost due to shoreline erosion.

A Business Opportunity Analysis (BOA) investigated product options for *Rhodiola* such as tea blends, extracts and pills and also the consumer target groups, including tourists, and manufacturers and retailers of natural health supplements. Operational logistics were also explored including agricultural production, post-harvest processing and adherence to Current Good Manufacturing Practice. While the plants are over-wintering in gardens, the growth and sustainability of the project is being analyzed and the Arctic Root team,

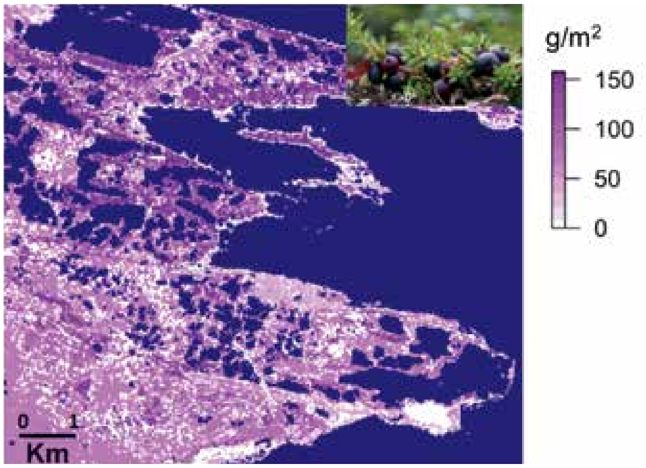

Figure 4. Map of an area around Arviat, Nunavut, showing spatial distribution of berry production in crowberry (Empetrum nigrum). Total production in the area shown (land area ca. 35 km^2) was estimated as 89,480 kg/y.

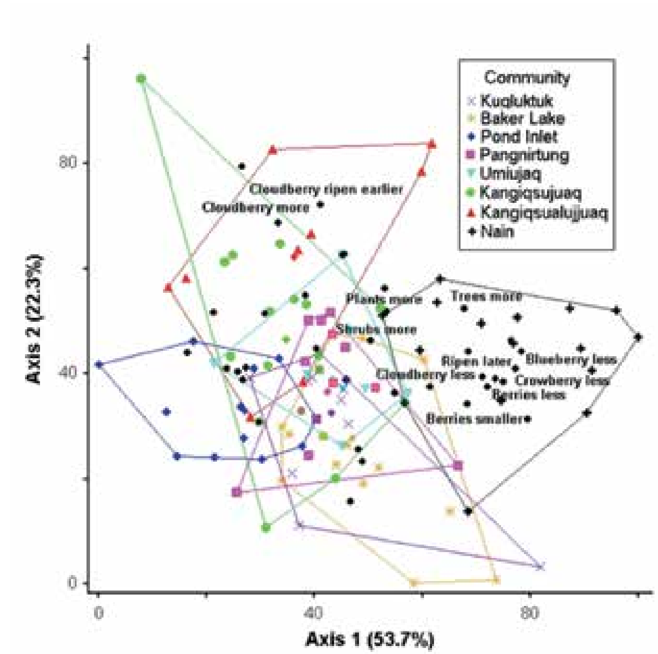

Figure 5. Ordination diagram (NMDS with Euclidean distance) showing separation of community observations regarding vegetation and berries from 144 interview participants, within and among eight Canadian Arctic communities. Responses for each community are shown by unique symbols, colours and convex hulls, which enclose points from a community. Environmental variables are shown with labels as closed black circles.

consisting biologists, business students, government officials and local knowledge holders is using the BOA and writing a comprehensive Business Plan. The plan will be shared with our scientific partners and then presented to the Nunatsiavut Government for possible future product development.

Syntheses and Database Activities

Preliminary results from our synthesis of berry productivity across the Canadian Arctic shows productivity is weakly correlated with regional climate, in contrast to local factors such as proximity to tall shrub cover or soil conditions (as shown in Figures 2 and 3).

As mentioned above and shown in Figure 5, a synthesis of Inuit observations of environmental change across eight communities in the Canadian Arctic shows that while there are common observations, such as less snow and earlier sea ice melt, there are regional differences in the changes.

Our discussions with Kwusen Research & Media (www.knowledgekeeper.ca) showed that their web based platform for archiving community-based knowledge in our communities could be useful to give communities the ability to control, access and share their information within and among communities. However, communication with communities and other agencies in the regional and territorial governments indicated that there may not be wide agreement on using this approach. Another potential web platform was presented by Joel Heath at the ArcticNet Annual Science Meeting in December, 2015 and we are in discussions with him about developing something similar for our project.

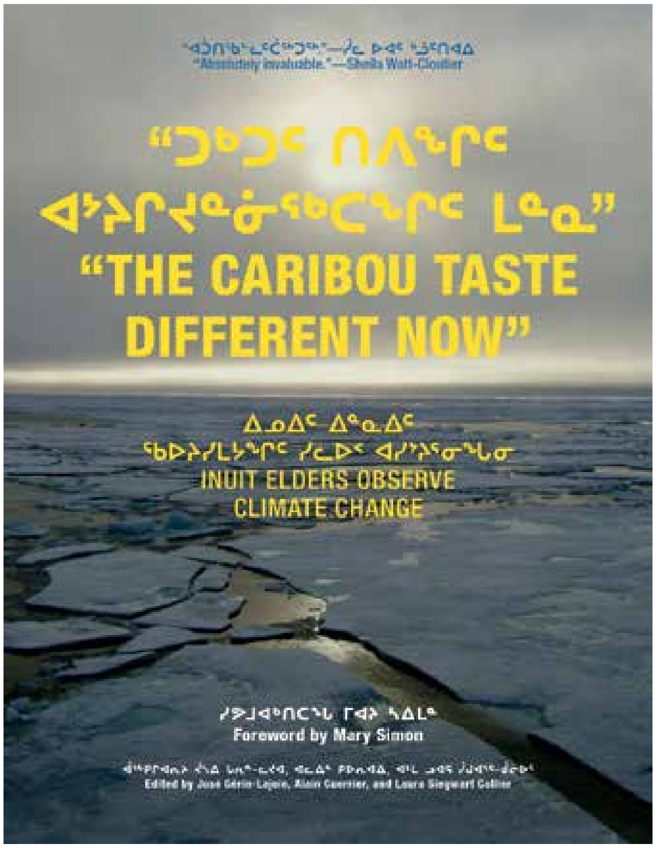

Figure 6. Cover of the book based on observations of environmental change made in eight Arctic communities during interviews held with elders and other community members over the course of 2007-2010. The book is set to be released in March 2016.

DISCUSSION

Tundra plant ecology and berry productivity and environmental change

Productivity of the four major berry producing shrub species we have studied is affected by local conditions. Production is best in open areas without shade but with good soil moisture, temperature and nutrient supply. Inside the canopy of tall shrubs there was a dramatic decrease in productivity, likely because of the shading by the dense canopy. As tall shrubs have been reported to be expanding in the forest-tundra and low Arctic tundra regions around the world in response to the warming climate (Myers-Smith et al. 2011) there is a growing concern that the cover and productivity of berry producing species will decrease over the coming decades. These results combined with the indications that berry production was decreased by experimental warming at some of our sites make further research and monitoring of berry production and vegetation change a high priority.

Gaining insights into the spatial variability of berry production across landscapes and their use by humans and wildlife in the vicinity of communities will help with future research and monitoring. Our results from the Arviat region indicate the berry production is robust and that consumption by humans and wildlife is a very small portion of the production. However, production could decrease in the future as these areas are prone to increased cover of tall shrubs in response to climate change (Myers-Smith et al. 2011; Elmendorf et al. 2012).

Community-based environmental monitoring

The network of permanent plots for measuring vegetation change and berry production in the vicinity of communities is vibrant, and was bolstered by the inclusion of the three LES modules in the science curriculum of Nunavik schools, and the new sites established near Sachs Harbour in the ISR. The variability in the productivity, which is currently being analyzed, is likely to be considerable across the Canadian Arctic, and may reflect some of the regional differences found in the Inuit observations of broader environmental changes. Students and other community members are generally pleased with the monitoring projects, and the results presented at Baker Lake and in Pond Inlet helped to reinforce the perceived value of the program. We expect the same responses when we present results in the other communities. The goal, ultimately, is to have the monitoring of environmental changes, including vegetation and berries, to be fully supported by the communities and regional agencies. The next stages will include broadening the environmental variables included in the monitoring and we can begin by using participatory mapping methods in select communities (Bennett and Lantz 2014).

Education and Outreach

The inclusion of the three LES modules into the science curriculum of the secondary schools in Nunavik is an important milestone in our project. This was one of our major goals in the original project, and we are delighted that our work is now part of the education materials in northern schools. One of the keys to maintaining the momentum in Nunavik will be the Avativut Mobile Teacher Training Workshop, which was held in two communities this past year. Giving the teachers the necessary background on the methods and the importance of the monitoring for the students and for science will help to ensure the success of the program.

Our discussions with Arctic College regarding the Avativut program in Nunavik shows there is potential to expand use of the protocols and concepts into the college programs, such as the Environment and Technology program. We will also continue to discuss the ideas in the Avativut program with appropriate people in education departments in Nunavut and Nunatsiavut.

The education goals of combining Inuit knowledge with science will also be aided by the publication of the book of Inuit observations of climate change and the berry book in Innuaqtun. Students in the eight communities and beyond will be able to relate their monitoring activities and results to the observations of their elders, and hopefully will gain a deeper understanding of their environment.

Natural health products: Rhodiola rosea

Labrador *Rhodiola rosea* was shown to be comparable in potency to commercially available (Eurasian) Rhodiola. Nunatsiavut Inuit community members support applying traditional knowledge towards a community-based enterprise and expect a range of valuable socio-cultural benefits to the community but only moderate economic gain. Our findings suggest that southerly gardens in Rigolet could be more successful than gardens in Nain, and also point to the need to learn more about the factors which support successful cultivation of *Rhodiola* in Nunatsiavut. The market for natural health products shows consistent growth, and Nunatsiavut *Rhodiola* would occupy a unique market niche. Linkages catalyzed by exploration of the opportunity to commercially cultivate Labrador *Rhodiola* include the Nunatsiavut Government, Enactus Memorial, the Food Security Network of Newfoundland and Labrador, the Genesis center, IRBV, ArcticNet, and the Harris Centre. Further research must be done to understand the conservation of Labrador *Rhodiola.*

Syntheses and Database Activities

The variability in observations of responses across the Arctic communities generally support the scientific analysis and modelling of climate change (IPCC 2014; Siegwart Collier et al. 2016 in prep). Geographic variation in precipitation is known to be difficult to model, although the general pattern of less precipitation in continental areas and the same or more in coastal areas is consistently reported (IPCC 2014).

Including our data on species composition and abundance into international databases is an important aspect of our project. We are pleased to see them being used in two recent syntheses related to ITEX, and we will continue to make our data available to other users.

The development of a web platform for the information and data we have collected during our ArcticNet project is another important objective for this final phase. It is clear that communities have differing views on the best way to accomplish this and to make it viable into the future. We have had to rethink our approach and will continue discussions with community members and appropriate agencies to ensure their will be a platform for communities to access and contribute to the information they have provided during our project.

CONCLUSION

- Berry productivity is decreased by the presence (shading) of a tall shrub canopy.
- The increased cover of tall shrubs in the future will negatively affect berry plants.
- The consumption of berries by humans and wildlife is a very small proportion of the total production of berries.
- The network of community-based monitoring of berry production and vegetation change across the Canadian Arctic continues to be strong, and was enhanced by the inclusion of Sachs Harbour, NWT, and by the adoption of the LES modules of the Avativut program in Nunavik schools.
- The variation in observations of environmental change by Inuit in communities across the Canadian Arctic generally concur with the scientific analyses.
- Publication of a book based on Inuit observations of climate change from interviews we conducted in eight communities (to be available in March 2016) will increase the transmission of knowledge from elders and other community members to Inuit and other youth.
- The cultivation of *Rhodiola* in Nunatsiavut will likely lead to a new business opportunity in the region based on the natural health benefits of the plant. Labrador *Rhodiola* will enjoy a unique market niche in part due to the distinctive local Inuit knowledge regarding the medicinal properties of the plant.
- Syntheses of our results are ongoing and will serve to better understand the spatial variability in berry production and the environmental changes observed by Inuit across the Canadian Arctic.
- Our data are being used in other global syntheses linked to ITEX.

ACKNOWLEDGEMENTS

Our research is not possible without the willingness of community participants in the various aspects of the project. The support provided by communities, regional, territorial and federal agencies, especially logistical support in the field, is a major part of the value added to our ArcticNet funding. Here we provide an incomplete list of the people and agencies across the Arctic and elsewhere who have helped with our work this past year.

Nunatsiavut

Communities of Nain and Rigolet. Nunatsiavut Government: Rodd Laing and Tom Sheldon. Parks Canada – Darroch Whittaker. Memorial University Enactus group – Victoria Allen.

Nunavik

Kativik School Board and 14 Nunavik High Schools, communities of Umiujaq, Kangiqsualujjuaq, Salluit, Inukjuak and Kangiqsujuaq. Lukassie Tooktoo and many others. Centre d'etudes Nordique, Université Laval.

Nunavut

Hamlets of Pond Inlet, Baker Lake and Arviat, Nunavut Research Institute, Arctic College, Inhabit Media, Jamal Shirely, Mary-Ellen Thomas, Jason Carpenter, Neil Christopher, Sean Guistini, Jessie Hale, Christian M. Fournier, Pascale Baillargeon, Hilda Snowball, Macombie Annanack, Ellen Avard, Élise Rioux-Paquette, Lilian Tran, Philippa Ootoowak. Danielle Black, Cassandra Elphinestone, Katriina O'Kane and Esther Frei. Polar Continental Shelf Program, Natural Resources Canada. Royal Canadian Mounted Police.

Inuvialuit Settlement Region

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Polar Data Management for Northern Science

Project Leader

Ellsworth LeDrew (University of Waterloo)

Collaborators

Christine Barnard (Centre d'études nordiques)
Leah Braithwaite (Environment Canada - Canadian Ice Service)
Yves Crevier (Canadian Space Agency)
David Hik (University of Alberta)
Scot Nickels (Inuit Tapiriit Kanatami)
Mathieu Ouellet (Fisheries and Oceans Canada - Integrated Science Data Management)
Peter Pulsifer (Inuit Tapiriit Kanatami)
David J. Scott (Natural Resources Canada - Geological Survey of Canada)
Scott Tomlinson (Aboriginal Affairs and Northern Development Canada - Northern Contaminants Program)
Warwick Vincent (Université Laval)

HQP

Yunwei Dong, Doctoral Student (University of Waterloo)
Aboyo Essi Enyonam, Doctoral Student (Institut des sciences de la mer de Rimouski, UQAR)
Ashley Stasko, Doctoral Student (University of Waterloo)
Donovan Bangs, Masters Student (University of Waterloo)
Julie Friddell, Research Associate (University of Waterloo)
Gabrielle Alix, Technical Staff (University of Waterloo)
David Friddell, Technical Staff (University of Waterloo)
Colline Gombault, Technical Staff (ArcticNet Inc.)
Frank Lauritzen, Technical Staff (University of Waterloo)
Garret Reid, Technical Staff (University of Waterloo)
Joshua Carlton, Undergraduate Student (University of British Columbia)
Colin Fagan, Undergraduate Student (University of Waterloo)
Abhina Mahendramohan, Undergraduate Student (University of Waterloo)
Tristan Mills, Undergraduate Student (University of Waterloo)

ABSTRACT

The Polar Data Catalogue (PDC) at the University of Waterloo is one of Canada's primary on-line sources for data and information on research in the polar regions. Formed as a partnership between ArcticNet, the Canadian Cryospheric Information Network (CCIN), the Department of Fisheries and Oceans Canada, and Noetix Research Inc., the PDC was created nearly 10 years ago as a long-term repository and online access portal to serve the data management needs of ArcticNet scientists and to facilitate the exchange of information among researchers, northern communities, international programs, the public, and other user groups. Since its online launch in 2007, the PDC has grown to include nearly 1800 descriptive records of datasets and polar data resources and 160,000 data files and satellite images from ArcticNet and a wide variety of other Canadian and international research and monitoring programs.

In this project, Polar Data Management for Northern Science, the PDC and CCIN will continue and extend the data management support that we provide to ArcticNet scientists and students who contribute their valuable data to the repository. We will streamline and simplify the data submission process by improving our online tools and will expand visibility of ArcticNet's data by sharing the PDC collections with other polar data portals through global interoperable linkages. We will seek new partnerships with northern partners and research and monitoring programs to coordinate polar data management in Canada and to ensure long-term relevance and sustainability. Along with increasing participation in the global data management community, these activities will secure ArcticNet's long-term data legacy and strengthen the PDC so that the ArcticNet data placed in the PDC now will be available for decades or centuries into the future.

KEY MESSAGES

- The development of the Polar Data Catalogue (PDC) and the ArcticNet data policy were initially motivated by the need for data sharing among ArcticNet researchers and with northern stakeholders.
- The PDC team works on continuous development and improvement of online tools and secure preservation infrastructure to help researchers share and preserve their data and to facilitate discovery, visualization, understanding, use, and long-term integrity of the data archived in the PDC.
- Each year, the focus on data sharing and proper management increases in the Canadian and international research communities. The PDC is a leader in Canada in building reliable infrastructure for archiving, serving, and sharing Arctic and Antarctic data and contributing to polar data management policies and best practices.
- Data management is rapidly becoming a formal requirement for research granting and coordination agencies around the world. For example, in 2015, the Canadian Tri-Council of research funding agencies released a Statement of Principles on Digital Data Management to guide data management activities for their funding recipients.
- The Polar Data Catalogue, co-developed by ArcticNet, the Canadian Cryospheric Information Network (CCIN) at the University of Waterloo, and numerous other contributing partners, places ArcticNet researchers at the forefront of meeting these evolving national and international expectations.
- Significant progress was made this year in inventorying datasets and working with researchers in ArcticNet and other partner programs to complete their metadata contributions to the PDC. In addition, more than

two million new data files, including ArcticNet datasets from the CCGS *Amundsen*, have been added to the PDC and are now available for public access and download.

- This year, the PDC, in collaboration with numerous partners, co-led two major data management meetings in Canada, the *Canadian Polar Data Workshop* (attended by 50 participants in Ottawa in May 2015) and the international *Polar Data Forum II* (attended by over 110 participants from 18 countries in Waterloo, Ontario in October 2015). These meetings have demonstrated Canadian leadership in polar data management and have laid the groundwork for increased collaboration and progress.
- Increasing partnerships and collaboration with Canadian and international data organizations are enhancing the connection of the PDC, and thus ArcticNet data and science, to the international data community and are creating new opportunities for funding and provision of PDC's data management services to new programs.
- Technical progress this year includes a complete rewrite of the online PDC Metadata/Data Input application to incorporate the latest web technologies, addition of a new Map Viewer in the PDC Geospatial Search application to display thousands of CTD casts from the CCGS *Amundsen*, and integration of Inuit feedback into improvements of the PDC Lite low-bandwidth data search application for use by northerners.

OBJECTIVES

To ensure ArcticNet's long-term data legacy, we aim to support ArcticNet and its researchers through continuation of effective data archiving and development of the PDC system. This project, Polar Data Management for Northern Science, continues to expand the data stewardship infrastructure first envisioned by ArcticNet and CCIN more than ten years ago. 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 projects' metadata records and data files in the PDC so that the legacy of ArcticNet research is available on the Internet for researchers, northern communities and organizations, international programs, and future generations;
- 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, to ensure long-term preservation and accessibility of the PDC data collections;
- Help lead the international effort to build an automatic polar metadata interoperability network to facilitate wide dissemination of the PDC collections and to make external research datasets and resources available to PDC users;
- 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 will make 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 for decades or centuries into the future.

CCIN and PDC will also pursue program-wide goals that will bring benefit to ArcticNet. We anticipate that activities to reach these goals will be co-funded by PDC partners, with the end result that all participants contribute to and benefit from enhancements to the PDC infrastructure and growing data archive. These additional goals are listed below:

- 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 school children, 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.

INTRODUCTION

Since its online launch in 2007, the Polar Data Catalogue (PDC, https://polardata.ca) has become Canada's primary on-line source for data and information on research in the polar regions. The PDC was initiated during Phase 1 of ArcticNet by members of Theme 2, in response to the need to facilitate data access for collaboration and synthesis and to meet the information needs of ArcticNet Network Investigators, partners, and stakeholders (Vincent et al., 2010). To build a data management system, ArcticNet partnered with the Canadian Cryospheric Information Network (CCIN, the current home of the PDC at the University of Waterloo where cryospheric data and information management have been ongoing since the mid-1990's), the Department of Fisheries and Oceans Canada (DFO), and Noetix Research Inc. to develop a "metadata database" of records describing research projects and datasets covering natural, social, and health sciences, 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.

Numerous programs support our mandates and have chosen the PDC to manage their data, making maximal use of partner-supported enhancements to the online PDC metadata and data input and search engine tools. Over the years, data stewards at the PDC and ArcticNet have worked with researchers and other data experts across Canada and the world to develop the PDC into a robust, internationally standards-compliant online database which meets the increasing demand for proper stewardship of valuable Arctic and Antarctic research datasets and information.

The PDC's commitment to data stewardship has been reinforced by the growing perception of government, funding agencies, publishers, and many scientists that data sharing and archiving should become a norm and a priority (http://www.icsu.org/general-assembly/news/press-release-2013-international-council-for-science-endorses-open-access-to-scientific-record-cautions-against-misuse-of-metrics). Continued development of the PDC will strengthen effective management of polar data in Canada and abroad.

Support from ArcticNet and other partners provides the ability to build and maintain a capable and respected archive for long-term access to and stewardship of Canada's polar research data. Advances in information technologies not only increase access to information but also allow data combination and synthesis 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 advancement of integrated data management systems.

The growing national and international profile of the PDC and the emphasis on data management by growing numbers of research organizations underscore 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. PDC's increased participation with the global community of scientific data managers enhances our services and expertise and facilitates wider dissemination of our data/metadata collection, placing ArcticNet and its researchers at the forefront of shaping national policy and of meeting evolving national expectations. This also ensures that Canada contributes to the success and coordination of polar data management around the world and ensures that PDC systems are carefully built and maintained so that the incoming data will be available as widely as possible now and for future generations.

ACTIVITIES

Specific tasks undertaken this year 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 data files for their projects, including data from the CCGS *Amundsen* for 2004-2015;
- Improved the PDC Metadata/Data Input, PDC Search, and PDC Lite online applications according to user input and improving technology, to enhance functionality and streamline future maintenance;
- Enhanced and maintained the CCIN/PDC computer infrastructure by updating server hardware, security, and backup functions, and explored opportunities for cloud-based offsite backup and/or operation with Compute Canada;
- Co-hosted the Canadian Polar Data Workshop and international Polar Data Forum II to coordinate and advance polar data management activities at the national and global scale;
- 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;
- Updated the process to assign Digital Object Identifiers (DOIs) to incoming ArcticNet metadata and datasets;
- Held workshops and made presentations to researchers, students, and other interested stakeholders on the importance of proper data stewardship, evolving expectations regarding sharing data, and accessing and contributing data to the PDC, including at the ArcticNet Annual Scientific Meeting;

- Worked with colleagues from polar data portals in Canada and in other countries to expand and standardize the automatic polar metadata interoperability network; and
- Continued development of the cost model to quantify the cost of data management at the PDC, using past data on expenditures for salary, hardware, travel, and other categories to produce a more accurate projection of future costs.

The tasks below have been co-supported from other sources and indirectly benefit ArcticNet through improved coordination and implementation of polar data management in Canada:

- Supported researchers in our partner programs to steward their metadata and data products, make them available in the PDC, and plan for the future of their programs;
- Formed partnerships with other polar research programs and the Arctic Science journal to increase the PDC data collections and user base;
- Enhanced the scientific and graphical content of the CCIN website, including updates to data visualizations and investigating options for modernization of the site;
- Sought arrangements for long-term support to sustain the PDC and pursued opportunities for significant new development funding;
- Designed and built new online data visualizations to make data within the PDC easier to use and understand;
- Improved our outreach through social media (Twitter, Facebook, and LinkedIn), brochures, and other avenues;
- Finalized the new snow hydrology data management system development begun in 2014 for a professor in the Geography department at the University of Waterloo, with entry of all data from her lab into the database, addition of new features to meet the needs of the professor and lab personnel, and completing and updating the User Manual to include all functions;
- Received RADARSAT satellite imagery from Antarctica and Greenland and began preparing them for inclusion in the PDC;
- Rescued data at risk of loss, including datasets from the International Polar Year program which ended in 2012; and
- Explored database alternatives to Oracle to facilitate offsite replication of the PDC database and system as we grow.

Metadata and Data Management and Stewardship

ArcticNet

With the new projects in place this year, input from ArcticNet scientists and students has intensified, with 164 new metadata records and 35 new datasets, for a total of 890 total approved metadata and 96 total datasets, comprising 2,441,104 datafiles. Further details are in the attached ArcticNet Project Metadata List and in the Results and Metadata sections of this report. The ArcticNet Administrative and Data Coordinator at U. Laval, C. Gombault, allocated considerable time to organizing and uploading to the PDC the diverse ship datasets collected on the CCGS *Amundsen* since 2003, particularly CTD (Conductivity-Temperature-Depth) and mooring data, to ensure their security and facilitate long-term archiving. The PDC Data Manager at CCIN in Waterloo, G. Alix, has assumed responsibility for review and approval of all ArcticNet metadata and data submissions. She makes numerous contacts with researchers, especially with respect to data preparation, submission, and review. She has reviewed outstanding ArcticNet metadata and data files and has approved them for public release, as appropriate.

Other programs

The PDC archives and serves online metadata and data for a variety of programs, including the Canadian government program for International Polar Year (IPY), the Northern Contaminants Program (NCP), the Beaufort Regional Environmental Assessment (BREA), and the Nunavut General Monitoring Plan (NGMP) of Indigenous and Northern Affairs Canada (INAC); Polar Knowledge Canada/Canadian High Arctic Research Station (POLAR/CHARS); Centre d'études nordiques (CEN); the Canadian Space Agency (CSA); Environment Canada and the Canadian Ice Service (EC/CIS); the Global Cryosphere Watch of the World Meteorological Organization (GCW/WMO); the Circumpolar Biodiversity Monitoring Program (CBMP); Takuvik; and others. Detailed metadata and data statistics for BREA, NCP, and other partner programs are found in the Results and Metadata sections of this report.

In our ongoing partnership with POLAR on developing a Data Policy for their program, we are working with experts to address remaining questions related to Traditional Knowledge and legal issues with sharing data. We have also developed Data Deposit/Access Agreements for use with POLAR researchers and others working in and around Cambridge Bay. We anticipate adaptation and use of these documents with NCP and NGMP, with the goal of coordinating policies across programs to simplify data stewardship for researchers, data managers, and users.

PDC Online Application Development

In 2015, along with security and usability improvements, the PDC Search GIS Viewer was significantly enhanced to display all publicly available ArcticNet CTD datasets from the CCGS *Amundsen* (Figure 1). The new Map Viewer provides a graphical interface for integrated display of multiple observations from the CTD casts.

The PDC Metadata and Data Input application has been completely rebuilt using the latest web technologies and tools. This major upgrade has required significant new development in the PDC database to accommodate a new web-database connection framework. The new application, which is currently being tested and is anticipated to go online in mid-2016, will feature enhanced security for PDC users and will incorporate the PDC glacier and logo into a simplified design which is mobile-device enabled and has a modern look (Figure 2).

Based on feedback from partners at Inuit Tapiriit Kanatami and individual users, we have updated the PDC Lite low-bandwidth Search application to improve the interface design, graphics, and text descriptions, including addition of local names and highlighting the four Inuit land claim regions in

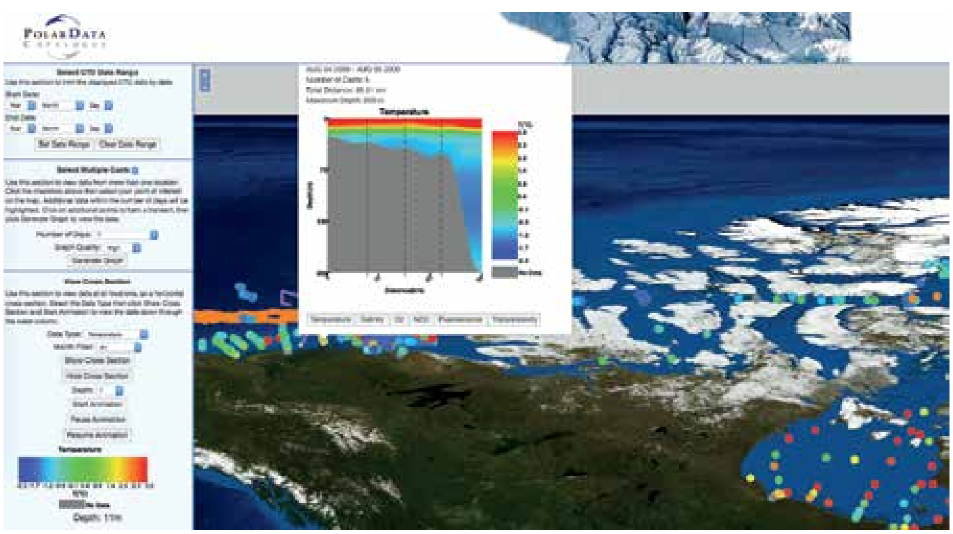


Figure 1. PDC Search Map Viewer, showing CTD datasets from the Amundsen.

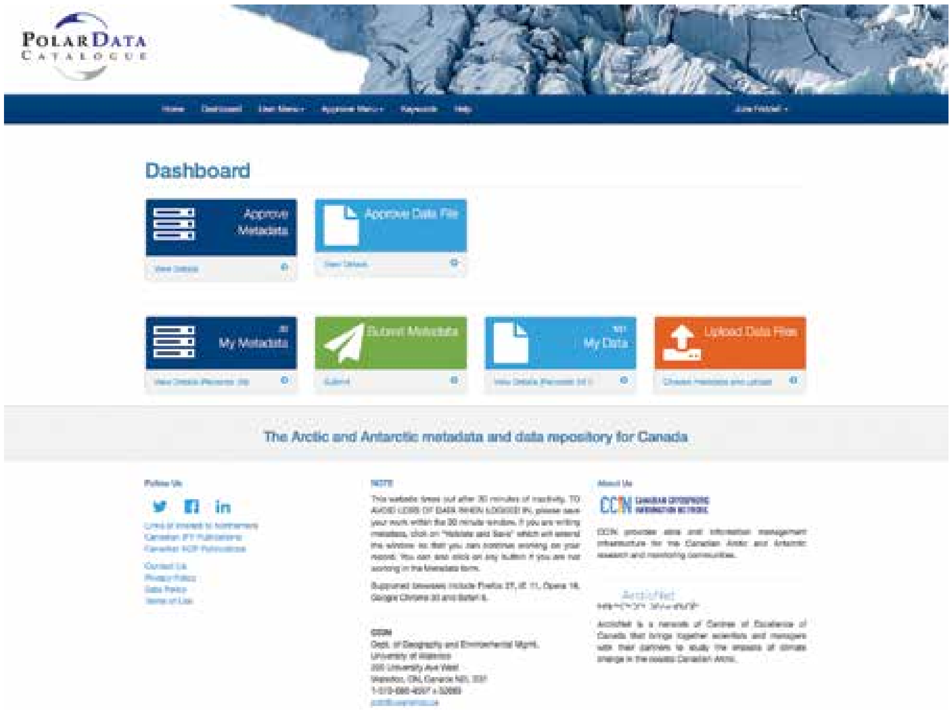


Figure 2. A prototype of the new PDC Metadata/Data Input application.

northern Canada (Figure 3). This Lite version of the PDC Search was originally developed in direct response to feedback and requests from northern stakeholders in ArcticNet. It is optimized for use in Internet-limited locations, such as many communities in northern Canada, and has been adapted to search for projects or information around a specific community. The PDC Help Manual has been updated to incorporate documentation on these and other new features which have been added during the past year.

Interoperability with other Polar Data Portals

This year, metadata sharing efforts focused on extending and solidifying existing linkages with polar data portals in Canada and abroad. Sharing metadata with other polar data repositories and web portals increases the visibility of PDC and ArcticNet data resources and facilitates scientific research and discovery. At this time, PDC metadata are provided for harvesting by other repositories in three different internationally-standardized web services protocols: OAI-PMH (Open Archives Initiative - Protocol for Metadata Harvesting), CSW (Catalog Services for the Web), and WMS (Web Map Service of the Open Geospatial Consortium). We have established 1-way or 2-way sharing links with approximately 20 portals (Figure 4) and are pursuing metadata and/or data interoperability with additional organizations. Specific activities are highlighted below:

- The three PDC metadata web services access points have been registered with the Global Earth Observation System of Systems - Group on Earth Observations (GEOSS-GEO) Component and Service Registry.
- To meet the specialized requirements of sharing with the Global Change Master Directory (GCMD) in the US, CCIN staff sent PDC metadata to GCMD for conversion to the GCMD format.
- Numerous discussions have taken place with personnel working with the Canadian

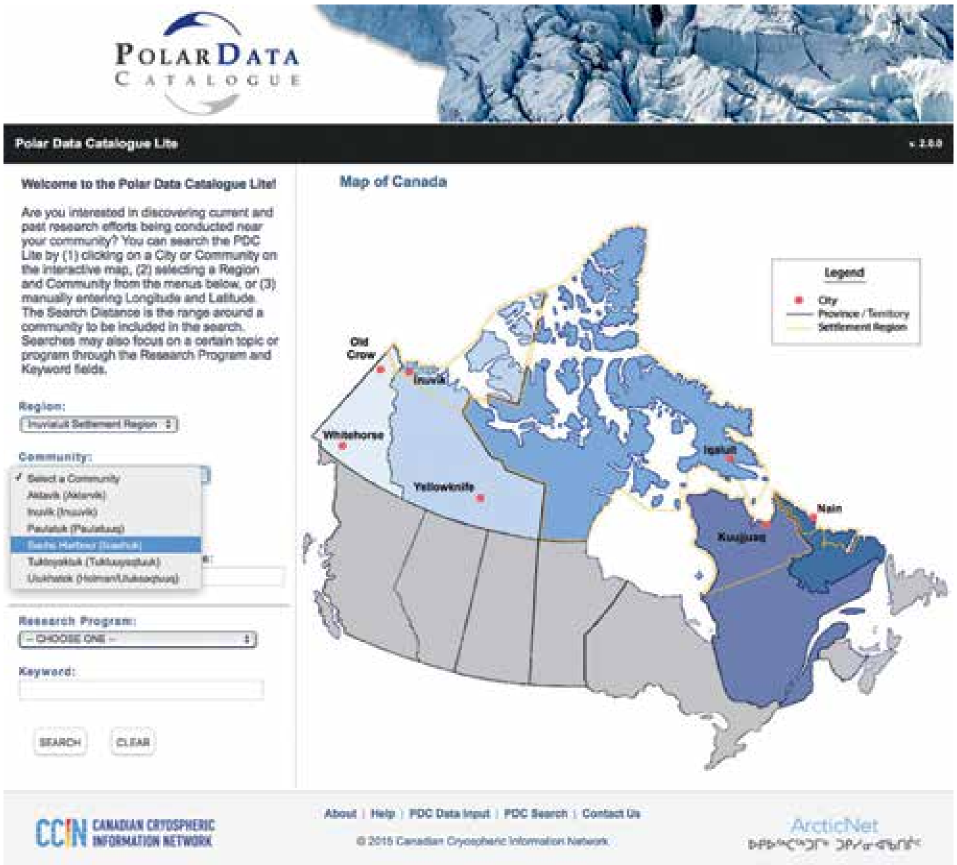


Figure 3. The PDC Lite's new map and search features.

government's Open Data website and the Federal Geospatial Platform, to explore options for registering PDC metadata and data in these federal systems.

Hardware, Infrastructure, and Security

The on-site CCIN hardware configuration at the University of Waterloo includes failsafe redundancy and continuous backup of data and software. The PDC data files, metadata, database, Java application code, and server and hardware configurations are duplicated in multiple locations onsite at the University of Waterloo as well as offsite for disaster recovery and protection against data loss. All PDC data and configurations have been successfully transferred to the 40 TB of offsite Compute Canada backup space at SHARCNET in Ontario that was awarded in early 2015. A new preservation system has been established at Scholars Portal, Ontario Council of University Libraries (SP/OCUL), headquartered at the University of Toronto. SP/OCUL previously held approximately 1.8 TB of PDC data files in a redundant backup capacity, but their new system has been configured to accommodate approximately 20 TB of PDC data files, allowing copy of most of the PDC collection to this offsite location.

In anticipation of replacing the CCIN/PDC computer server and storage infrastructure once it reaches end of life in a few more years, CCIN staff have been exploring options for transferring all CCIN and PDC systems and collections to an offsite cloud-based location. This year, we have had extensive discussions with Compute Canada and Compute

Figure 4. PDC's metadata sharing partners.

Ontario/SHARCNET to understand their capabilities for storing and serving the CCIN/PDC system via their infrastructure. At the current time, it is not clear whether this will provide an acceptable solution, so we have begun discussions with computer hardware vendors to estimate the cost of replacing our on-site system. If we do move onto the cloud, it will be necessary for the PDC/CCIN to move to a new database system, since the Oracle software that we currently use is only available for use on the University of Waterloo campus. 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 this year we have built a new test database server, installed PostgreSQL (an open-source alternative to Oracle), and have compiled the tools necessary to begin the transition away from Oracle.

Support and New Partnerships

Successful proposals or letters of intent to support and expand PDC and CCIN activities were prepared this year for existing and new partners at NCP, POLAR, NGMP, ArcticNet, Environment Canada, and Compute Canada. Support for partial salary of the CCIN Associate Director has also been provided by the Faculty of Environment of the University of Waterloo. Unsuccessful proposals were sent to the Canadian Space Agency, the Horizon 2020 program of the European Commission, and the Science and Technology division of Environment Canada. We will continue to pursue opportunities with these organizations as well as the new Arctic Science journal (to be the archive for datasets associated with articles), the Walter and Duncan Gordon Foundation (to archive the data resulting from their new Mackenzie Data Stream of water quality data), and others.

Figure 5. Canadian Polar Data Workshop participants.

Recent proposals, under review, have been prepared for the Canadian Foundation for Innovation's (CFI) new cyberinfrastructure initiative and the Social Sciences and Humanities Research Council of Canada (SSHRC, two proposals, one for the Arctic Marine Use and Transportation Project (AMUT), a Canadian consortium led by Jackie Dawson of the University of Ottawa). The second SSHRC proposal and the CFI proposal are in support of a new multi-institution partnership in Canada for Arctic data management led by the Arctic Institute of North America at the University of Calgary called CCADI, the Canadian Consortium for Arctic Data Interoperability. The budgets for both of these proposals are in the millions of dollars, and the project lengths are from three to five years, so success in these proposals would translate to long-term support for realizing significant enhancements to our technical cyberinfrastructure as well as partnerships with polar organizations and northerners in Canada that we have envisioned for many years.

Second Polar Data Forum - Communiqué

International Collaboration for Advancing Polar Data Access and Preservation
27-29 October 2015, Waterloo, Ontario, Canada
http://www.polar-data-forum.org/

The Importance of the Polar Regions for Humankind

The polar regions are experiencing dramatic change. Understanding their complex dimensions (environmental, climatic, social, economic, and geophysical) is critical to grasping the global system and defining our future. Data are an invaluable resource. The coordinated capture, analysis, storage, stewardship, and sharing of scientific data along with Indigenous knowledge helps society better understand the regional and global impacts of polar changes. But these data management activities present considerable technical, social, policy, and economic challenges.

The Second Polar Data Forum

In October 2015, more than 110 people gathered at the Second Polar Data Forum (PDF II) at the University of Waterloo, Canada, to address these challenges. Data managers, scientists, funding program managers, Indigenous people and their representatives, students, and others from eighteen nations shared their knowledge, experience, and ideas on how to make polar data more useful and valuable in solving global problems.

Photo Credit: Marten Tacoma

In 2013, at the First Polar Data Forum (PDF I) in Tokyo, Japan, the community identified issues and made observations and recommendations on polar data management. PDF I focused on improving how people and systems can share data in a meaningful way. The goal was to move towards open and connected systems based on a culture of trust and acknowledgement of data production and use.

PDF II highlighted the significant progress in polar data management made since PDF I and also identified priorities as we move forward. The community reconfirmed the themes of PDF I, identified key new themes that have evolved, and planned a set of action-oriented recommendations and activities.

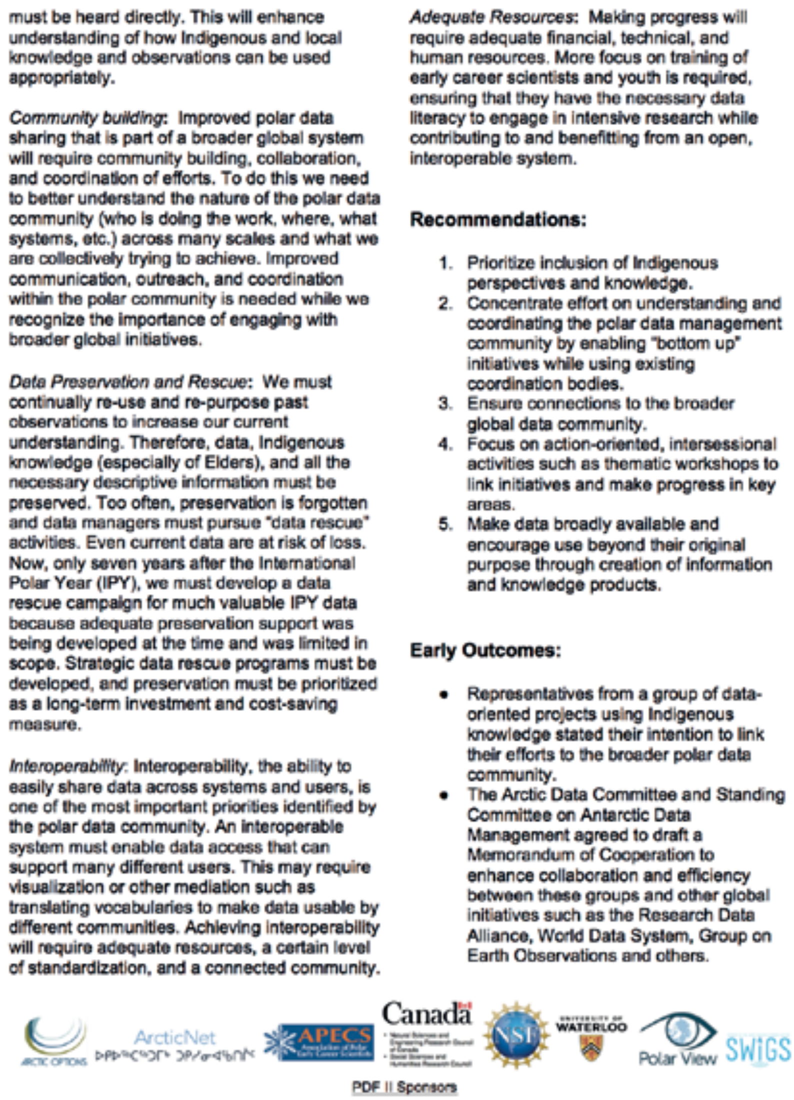
Key Themes Emerging from PDF II

Including Arctic Indigenous Perspectives: In this time of change, Indigenous knowledge and the underlying observations of Arctic peoples are more important than ever. Along with the knowledge of non-Indigenous local inhabitants, this knowledge is being increasingly documented and represented as digital data, but the nuances of these data are not well understood by the broader data management and science community. The perspectives of Indigenous people and other northern residents

Figure 6a. Polar Data Forum II Communiqué.

Outreach, Communication, and Service

The CCIN/PDC Facebook, Linkedin, and Twitter accounts have been used more extensively this year to post relevant news articles and to announce CCIN and PDC news, including improvements to the PDC applications, new publications, and participation in conferences and events. On Twitter, we have 193 followers, and we have made over 2,300 tweets since creation of the account in 2011. This past year, we developed a Social Media Strategy to increase our outreach and visibility to our current partners and new users. One of the new goals is to increase the use of the PDC Facebook page, to provide information on data


must be heard directly. This will enhance understanding of how Indigenous and local knowledge and observations can be used appropriately.

Community building: Improved polar data sharing that is part of a broader global system will require community building, collaboration, and coordination of efforts. To do this we need to better understand the nature of the polar data community (who is doing the work, where, what systems, etc.) across many scales and what we are collectively trying to achieve. Improved communication, outreach, and coordination within the polar community is needed while we recognize the importance of engaging with broader global initiatives.

Data Preservation and Rescue: We must continually re-use and re-purpose past observations to increase our current understanding. Therefore, data, Indigenous knowledge (especially of Elders), and all the necessary descriptive information must be preserved. Too often, preservation is forgotten and data managers must pursue "data rescue" activities. Even current data are at risk of loss. Now, only seven years after the International Polar Year (IPY), we must develop a data rescue campaign for much valuable IPY data because adequate preservation support was being developed at the time and was limited in scope. Strategic data rescue programs must be developed, and preservation must be prioritized as a long-term investment and cost-saving measure.

Interoperability: Interoperability, the ability to easily share data across systems and users, is one of the most important priorities identified by the polar data community. An interoperable system must enable data access that can support many different users. This may require visualization or other mediation such as translating vocabularies to make data usable by different communities. Achieving interoperability will require adequate resources, a certain level of standardization, and a connected community.

Adequate Resources: Making progress will require adequate financial, technical, and human resources. More focus on training of early career scientists and youth is required, ensuring that they have the necessary data literacy to engage in intensive research while contributing to and benefitting from an open, interoperable system.

Recommendations:

1. Prioritize inclusion of Indigenous perspectives and knowledge.
2. Concentrate effort on understanding and coordinating the polar data management community by enabling "bottom up" initiatives while using existing coordination bodies.
3. Ensure connections to the broader global data community.
4. Focus on action-oriented, intersessional activities such as thematic workshops to link initiatives and make progress in key areas.
5. Make data broadly available and encourage use beyond their original purpose through creation of information and knowledge products.

Early Outcomes:

- Representatives from a group of data-oriented projects using Indigenous knowledge stated their intention to link their efforts to the broader polar data community.
- The Arctic Data Committee and Standing Committee on Antarctic Data Management agreed to draft a Memorandum of Cooperation to enhance collaboration and efficiency between these groups and other global initiatives such as the Research Data Alliance, World Data System, Group on Earth Observations and others.

PDF II Sponsors

Figure 6b. Polar Data Forum II Communiqué.

and resources to northerners who use Facebook quite heavily.

To receive additional feedback on our websites, we created brief surveys, which were reviewed for ethics compliance by the University of Waterloo, for the CCIN website and the three PDC applications. We sent the surveys to over 180 researchers, students, and policy makers and received 17 responses with suggestions for improvements to our sites. We have a list of 25 northerners to whom we did not send the questionnaires yet as we seek to coordinate this activity with ITK. We would like to increase the response rate, so we are exploring other methods, including online surveys like Survey Monkey, so that we can receive more complete and useful feedback and input for improvements.

Presentations were made at international and Canadian conferences as follows:

- Friddell, J., Data Management for Geographic Science. Oral presentation, Geography and Planning 387 course (Spatial Databases), University of Waterloo, Waterloo, ON (February 2015).
- Friddell, J., Progress in Creating a Global Polar Metadata Interoperability Network. Oral presentation, Environment Climate Data Sweden Seminar on Open Access and E-Infrastructure, Stockholm, Sweden (March 2015).
- Friddell, J., Data Management for Geographic Science. Oral presentation, Geography 600 (Seminar in Spatial Data Handling), University of Waterloo, Waterloo, ON (March 2015).
- Alix, G., Review of Questionnaire Responses. Oral presentation, Canadian Polar Data Workshop, Ottawa, ON (May 2015).
- Friddell, J., Interoperability - a Challenge for Polar Data Management in Canada. Oral presentation, Canadian Polar Data Workshop, Ottawa, ON (May 2015).
- Alix, G., How to Prepare Good Metadata and Data for Sharing and Archiving. Oral presentation, Associate of Polar Early Career Scientists' World Summit, Sofia, Bulgaria (June 2015).
- Alix, G., The Polar Data Catalogue. Oral presentation, Association of Polar Early Career Scientists (APECS) World Summit, Sofia, Bulgaria (June 2015).
- Alix, G., Perspective of a Data Manager on Managing Research Data. Oral presentation, Open Access Day, Waterloo, ON (October 2015).
- Alix, G., How to Prepare Good Metadata and Data for Sharing and Archiving. Oral workshop presentation, Polar Data Forum II, Waterloo, ON (October 2015).
- Friddell, J. and G. Alix, Where Can I Find Data for my Research? The Polar Data Catalogue and the Global Data Sharing Network. Oral presentation, Cryospheric Sciences Research Group, University of Waterloo, Waterloo, ON (November 2015).
- Friddell, J., Ocean Data Visualization at the Polar Data Catalogue. Oral presentation, MEOPAR Ocean Data Management Expert Forum, Montréal, QC (November 2015).
- Friddell, J. and G. Alix, How to Prepare Good Metadata and Data for Sharing and Archiving. Two oral workshop presentations, ArcticNet Student Association Student Day, ArcticNet Annual Scientific Meeting, Vancouver, BC (December 2015).
- LeDrew, E., J. Friddell, and G. Alix, Accessing, Sharing and Preserving Polar Information: A Transformative Process for Canada's Polar Regions and The Polar Data Catalogue: Data Stewardship for POLAR & Canada. Two oral presentations to the Board of Polar Knowledge Canada, Vancouver, BC (December 2015).

In addition, J. Friddell, CCIN Associate Director, served in the following capacities:

- Canadian representative, Arctic Data Committee of the International Arctic Science Committee and Sustaining Arctic Observing Network, leading a project on standardizing the minimum information required for effective metadata sharing
- Member, Canadian Tri-Agency Data Management Policy Advisory Committee
- Member, Scientific Advisory Committee, Environment Climate Data Sweden
- Session co-convener, Sharing Arctic Data, Observations and Knowledge: Understanding the Global System through International Exchange, Fourth International Symposium on the Arctic Research and the Third International Conference

on Arctic Research Planning, Toyama, Japan, April 2015

- Reviewer, Earth System Science Data open-access journal
- Participant in User Requirements workshop, Polar View Earth Observation Limited's Polar Thematic Exploitation Platform project of the European Space Agency, Innsbruck, Austria, September 2015
- Co-chair, breakout session on Building Integrated International Research Data Collections and Access Systems, 2nd Tri-lateral Symposium on Arctic and Marine Research Infrastructure, Halifax, September 2015
- Chair, Local Organizing Committee, Polar Data Forum II, Waterloo, October 2015

Canadian and International Polar Data Management Activities and Strategic Planning

Along with numerous other partners and organizations, the PDC/CCIN co-hosted a Canadian Polar Data Workshop (CPD Workshop) in Ottawa in May 2015 to help coordinate the growing polar data community in Canada and to develop and implement best practices and sustainability in data stewardship. The Workshop agenda was crowd-sourced through a six-week national consultation on polar data, in the form of an online survey answered by individuals from 30 organizations. The Workshop was attended by 44 people, and six more individuals joined remotely (Figure 5). Presentations were made on data management topics and challenges, including data sharing, access, preservation, interoperability, policy, funding, and partnerships, and breakout groups gathered participants' ideas on needs and activities of Canada's polar data community. In addition, national coordination and contribution to the international polar data community were discussed at length. The primary outcomes are creation of a report on the Workshop and the landscape of polar data activities in Canada, new opportunities for collaboration, and a position paper representing the views of the community and significant issues. The position paper will be actively shared with government agencies, academia, northern Canadian organizations, funding bodies, and other stakeholder groups with connections to or responsibility for management of polar data in Canada. The long-term goal is to design and implement, through consensus of the participants, a national management plan and structure for coordination of our activities and systems.

In October 2015, co-chaired by P. Pulsifer and E. LeDrew, Polar Data Forum II: International Collaboration for Advancing Polar Data Access and Preservation (http://www.polar-data-forum.org) was co-hosted by CCIN/PDC and many international research and data organizations at the University of Waterloo. Over 110 data managers, researchers, students and early career researchers, northern residents, policy and funding agency representatives, and others from 18 countries participated to collaborate on improving access to Arctic and Antarctic data and information. The University of Waterloo Aboriginal Student Association opened the Forum with several songs with drums, and an Aboriginal Evening included a local women's drum circle, a smudging ceremony, and locally sourced Indigenous foods. Results from the Canadian Polar Data Workshop and national consultation were presented, and other examples of effective community coordination abroad were presented which will be very helpful to our efforts in Canada. In addition, a Data Management workshop focused on graduate students was led by PDC staff, the annual meetings of the IASC/SAON Arctic Data Committee and the Standing Committee on Antarctic Data Management of the Scientific Committee on Antarctic Research (SC-ADM/SCAR) were held, and several other groups used the opportunity to hold side meetings, making the event a very busy and reportedly very successful 6-day Polar Data Week in Waterloo. The key themes that emerged from the meeting, as described in the PDF II Communiqué (http://polar-data-forum.org/programme/PDFII_Communique_FINAL.pdf and Figure 6), include coordinating and building community, preserving and rescuing data, including Arctic Indigenous perspectives, facilitating interoperability, and providing adequate resources. Finally, a Special Issue of CODATA's Data Science Journal with articles from the PDF II is in process, with P. Pulsifer, E. LeDrew, and J. Friddell serving as guest co-editors for the issue.

Support for the Polar Data Forum II was received through awards from the Natural Sciences and Engineering Research Council (NSERC), SSHRC, and the US National Science Foundation (through the University of Colorado). Generous contributions from ArcticNet, Polar View Earth Observation Limited, the University of Waterloo, and the Association of Polar Early Career Scientists were critical to the success of both the Forum and the CPD Workshop.

The PDC's Polar Data Management Committee (PDMC) held an informal meeting in October during the Polar Data Forum and had a face-to-face meeting at the ArcticNet Annual Scientific Meeting in Vancouver in December. At the ArcticNet Student Day event, E. Aboyo replaced A. Stasko as the elected ArcticNet Student Association liaison. P. Pulsifer was nominated to be a second co-chair of the committee, following W. Vincent stepping down last year. Following discussions during PDMC meetings as well as at the Canadian Polar Data Workshop and ongoing planning for the future of CCIN/PDC with the University of Waterloo administration, the structure and membership of the PDMC may be revised to better serve the evolving needs of both the PDC and the polar data community in Canada. Options under discussion include splitting the Committee into advisory and management components and expanding the Committee's mandate to represent more than just the PDC.

Through the Workshop and Forum events this year, we have seen great interest by large numbers of stakeholder organizations in coordinating the polar data community both in Canada and internationally, and the community has been recognized as a leader in working together to facilitate streamlined data systems for improving access to polar data. To continue the momentum and address the themes and challenges highlighted by these meetings, we continue to engage with the Tri-Council, primarily NSERC and SSHRC, to promote data management and support for data-related activities throughout their programs. We expect to advance this activity in 2016 and to engage with all of our partners on strategic planning to secure the long-term future of the PDC.

RESULTS

Metadata and Data in the PDC

As of 2 February 2016, the number of PDC metadata records from all programs reached 2,512, with 21 in the SUBMITTED state, two in the SENTBACK state, 99 in the SAVED state, and 2,390 APPROVED and available publicly. Outreach to metadata contributors has been increasing this year and has resulted in a nearly 50% reduction in SAVED metadata for ArcticNet and other programs. This year, ArcticNet scientists and students have contributed 164 new metadata records, for a total of 890 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: 90
- CBMP (including over 300 new metadata from the Terrestrial program entered in 2015): 527
- IPY (many researchers are publishing the results of their IPY research and are now ready to archive their data in the PDC): 728
- CASES (Canadian Arctic Shelf Exchange Study): 84
- ADAPT (Arctic Development and Adaptation to Permafrost in Transition): 81
- NCP (INAC): 135

- BREA (INAC): 134
- APAN (Adaptation Program for Aboriginals and Northerners, INAC): 121
- NGMP (INAC): 17
- POLAR (Polar Knowledge Canada): 38
- Reference (for other polar-related data and information portals and websites from around the world): 71

To date, 283 datasets have been submitted to the PDC archive, 96 of which are affiliated with ArcticNet. Thirty-five of these ArcticNet datasets have been added this year, for a total of 2,441,104 data files. Of all the archived data, 245 are available online, with the remainder either not available publicly due to privacy issues or temporary embargoes or due to ongoing efforts required to properly organize and archive the files. There is a total of 2,675,356 data files in the PDC, approximately 30 Terabytes in total, consisting of 18.2 TB of files from research datasets, 6.5 TB of RADARSAT imagery, and 5.2 TB of data files in our server that are waiting to be processed, reviewed, and approved before they are available on the PDC.

Outreach and Publications

In addition to the many presentations and published conference abstracts, three news articles and short items about the PDC and our data collections were published in newsletters and online magazines:

- G. Reid, Open Data Portals and Geomatics – The Polar Data Catalogue. GoGeomatics Canada Magazine, http://www.gogeomatics.ca/magazine/open-data-portals-and-geomatics-the-polar-data-catalogue.htm, June 2015.
- Several news items on the Polar Data Catalogue, metadata harvesting and interoperability between PDC and CBMP, and the Polar Data Forum II, Circumpolar Biodiversity Monitoring Program Newsletter, http://archive.constantcontact.com/fs150/1102157694644/archive/1120991966569.html, Spring 2015.
- Balasubramaniam, A., Polar Data: Key challenges faced by an evolving paradigm. Polar Leads brief report, Polar Knowledge Canada and APECS Canada, https://www.canada.ca/en/polar-knowledge/publications/polarleads/vol1-no2-2015.html, November 2015.

Also, a 2-page folding brochure was created with introductory information on the PDC applications and the CCIN website and was distributed at conferences and meetings.

DISCUSSION

The PDC continues to evolve into a reliable and recognized repository and access website for ArcticNet metadata and data as well as data and information from Canada's other Arctic and Antarctic research programs. Major accomplishments this year were a dramatic increase in the number of data files in the PDC repository (from approximately 200,000 to over 2.6 million files), addition of new metadata from ArcticNet's new 2015-2018 projects, complete modernization of the PDC Metadata/Data Input application, and co-hosting two successful meetings on Canadian and international activities to improve polar data management.

Discussions continue with a growing number of organizations regarding collaborating on polar data management efforts and serving new groups' data stewardship needs, with significant new relationships with several academic, northern, government, and publishing organizations. The PDC's involvement and contributions to the polar data community are also growing through formal partnerships with an increasing number of Canadian and international institutions. PDC staff are benefiting from these closer interactions as we gain knowledge and provide expertise to improve data management both at the PDC and with our partners.

CONCLUSION

Each year, data management is becoming a formal requirement for more and more research granting, coordination, and publishing agencies around the world. The Polar Data Catalogue, co-developed by ArcticNet, CCIN, and many other contributing partners, prepares ArcticNet researchers and places them at the forefront of successfully meeting the evolving data management requirements and expectations of the Canadian research community. Continued development of the PDC, via support from ArcticNet and other partners, is strengthening effective management of Arctic and Antarctic data in Canada and providing the ability to build and maintain a capable and respected archive for long-term access to and stewardship of Canada's polar research data.

The growing maturity of the PDC platform, and the expectation that we will be available to researchers and users for the very long term, gives us the confidence and leverage to work with sponsors toward a sustainable future for the PDC and its data collections. Our commitment to incorporation of international standards for discovery and interoperability has positioned the PDC to be a contributor to the future of data management, and our progress is being increasingly recognized at the national and international levels. Linking the PDC to Canada's and the rest of the world's polar data portals is creating strong links to the global community of polar data managers. Maturity of this global network increases the service that we can provide and gives support to all stakeholders involved in polar data management, including PDC staff members, ArcticNet and other Canadian and international researchers, and Canada's northern Indigenous people.

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Knowledge Co-Production for the Identification and Selection of Ecological, Social, and Economic Indicators for the Beaufort Sea

Project Leader

Lisa Loseto (Fisheries and Oceans Canada - Freshwater Institute)

Network Investigators

Steven Ferguson (University of Manitoba)
James Ford (McGill University)
Emily Jenkins (University of Saskatchewan)
Tristan Pearce (University of the Sunshine Coast)
Gary A. Stern (University of Manitoba)

Collaborators

Carolyn Bakelaar (Fisheries and Oceans Canada - Central & Arctic Region)
Connie Blakeston (Fisheries and Oceans Canada - Central & Arctic Region)
Peter Collings (University of Florida)
Andrew Doolittle (Fisheries and Oceans Canada - Central & Arctic Region)
Vic Gillman (Fisheries Joint Management Committee (FJMC))
Lois Harwood (Fisheries and Oceans Canada - Central & Arctic Region)
Kristin Hynes (Fisheries Joint Management Committee (FJMC))
Adam Kudlak (Hamlet of Ulukhaktok)
Stéphane Lair (Université de Montréal)
Marianne Marcoux (Fisheries and Oceans Canada - Central & Arctic Region)
Steve Newton (Fisheries and Oceans Canada - Freshwater Institute)
Ole Nielsen (Fisheries and Oceans Canada - Central & Arctic Region)
Shannon O'Hara (Inuvialuit Regional Corporation)
Diane Ruben (Paulatuk Hunter and Trappers Committee)
Bob Simpson (Inuvialuit Regional Corporation)
Kathleen Snow (Fisheries and Oceans Canada - Central & Arctic Region)
Rashid Sumaila (University of British Columbia)
Danny Swainson (Fisheries Joint Management Committee (FJMC))
Scott Tomlinson (Aboriginal Affairs and Northern Development Canada - Northern Contaminants Program)
Jill Watkins (--)
Dustin Whalen (Natural Resources Canada - Geological Survey of Canada (Atlantic))

HQP

Emily Choy, Doctoral Student (Fisheries and Oceans Canada - Freshwater Institute)
Identifying the Seasonal Diet of Eastern Beaufort Sea Belugas and the Bioenergetic Consequences of Climate Change
Jeremy Bentley, Honours Undergraduate Student (Dalhousie University)
Jasmine Brewster, Masters Student (University of Manitoba)
Claire Hornby, Masters Student (University of Manitoba)
Eric Lede, Masters Student (Trent University)
Devin Waugh, Masters Student (University of Guelph)
Carie Hoover, Post-Doctoral Fellow (University of British Columbia)
Sonja Ostertag, Post-Doctoral Fellow (McGill University)
Vanessa Grandmaison, Technical Staff (University of Manitoba)
Paden Lennie, Undergraduate Student (Fisheries Joint Management Committee (FJMC))

Northern HQP

Andrew Gordon Jr., Northern Research Staff (Fisheries Joint Management Committee (FJMC))
Brandon Green, Northern Research Staff (Paulatuk Hunter and Trappers Committee)
Jody Illasiak Sr, Northern Research Staff (Paulatuk Hunter and Trappers Committee)
John Noksana Sr, Northern Research Staff (Tuktoyaktuk)
Roland Notaina, Northern Research Staff (Hamlet of Ulukhaktok)
Devalynn Pokiak, Northern Research Staff (Tuktoyaktuk)

ABSTRACT

This network aims to bridge multiple stakeholders, management agencies, and knowledge holders to effectively link ecological changes to the greater health of the ecosystem at the local, regional and circumpolar scales. Arctic ecosystems not only support human well-being and contribute to economies, but they are also under increasing pressure from climate change and resource use. The Inuvialuit Settlement Region (ISR) is home to six communities that rely on resources within the Beaufort Sea for activities such as hunting, trapping, fishing, and whaling. This research program aims to use a multiple evidence based (MEB) approach to bridge diverse knowledge systems, for the development of a comprehensive set of indicators to monitor the marine ecosystem. The overall goal of integrating information across knowledge systems and disciplines will first occur at the local level to develop a better understanding of beluga health and habitat use. This will then be used to develop indicators so assist co-management boards with decision-making. In the second phase, the MEB approach will be used at a regional scale to integrate indicators across social, ecological, and economic disciplines to select a suite of indicators to be used to inform decision-making at the local, regional, and circumpolar levels. In order to manage natural resources effectively, management entities (Oceans Canada, Fisheries Joint Management Committee) are working to select indicators to be used as proxies for identifying change in the region. These include ecological indicators to identify changes in the ecosystem and environment, social indicators to identify changes occurring within the local communities, and economic indicators to identify changes regarding economic activity. The results from this program will enhance marine mammal and ecosystem monitoring in the Arctic by providing insight into processes that foster the coproduction of knowledge towards an improved understanding of the marine ecosystem. In addition, key indicators identified through this program will feed into regional, national and international monitoring programs.

KEY MESSAGES

- Inuit have a highly detailed and holistic understanding of the marine ecosystem, which taken together with western scientific understanding can develop more robust and accurate indicators and monitoring programs.
- Management objectives and targets must be clearly defined for setting management priorities in order for indicators to be relevant.
- Among the 14 co-management agencies with marine governance responsibility in the Inuvialuit Settlement Region (ISR) 398 marine resource management objectives were obtained from 1833 documents. Only 5% of these objectives were classified as having specific and measurable targets to enable appropriate indicator selection.
- Priorities were established for regional indicators across different categories with input and ranking from key stakeholders. From this high priority regional goals will be used for future indicator assessments and selection.
- Developed protocol for co-production of knowledge at the regional scale, highlighting the inclusion of co-management agencies and key stakeholders within the region.
- Inuvialuit knowledge and understanding of beluga health and habitat use was documented.
- The health of beluga whales from an Inuvialuit perspective was determined in part by the appearance and behaviour of the whales during harvesting activities, the condition of muscle, muktuk and blubber and, the appearance of internal organs.
- Inuvialuit participants shared knowledge about beluga calving areas, potential nursery areas, feeding areas and travel routes/times in the areas surrounding their communities and harvest sites.
- In Ulukhaktok, where beluga harvesting is a more recent activity, social learning is underway for beluga hunting techniques and food preparation.

- There are opportunities for inter-community teaching and learning of beluga hunting and food preparation between Inuit in Ulukhaktok and Inuvialuit hunters in the Mackenzie Delta.
- In Ulukhaktok, Inuit observe the presence of beluga whales as an indicator of change in the marine ecosystem with cascading effects.

OBJECTIVES

We continued with the objectives identified in our proposal; note that our Year 1 was focused on the components that support the following overarching objectives.

- Develop and implement a framework for the co-production of knowledge for the identification and interpretation of indicators at the local scale.
- Scale from local to regional indicator development for the Beaufort Sea ecosystem.
- Develop, test and validate a set of regional ecosystem indicators based on different user objectives.
- Evaluation of knowledge co-production into indicator selection at the local and regional scale.
- Integrate indicators into a decision-making tool to strengthen linkages between research and policy.

INTRODUCTION

Climate change impacts will have implications for ecosystems and the human communities that depend on them (Larsen et al. 2014), and models project that these changes will continue, and in some instances accelerate in the future (Collins et al. 2013). The cumulative impacts of climate change and multiple anthropogenic stressors (e.g. resource exploration and exploitation) have put arctic marine ecosystems under increasing pressure (SWIPA 2011). The rapid nature of these changes heightens the urgency to identify ways to sustainably manage and govern these ecosystems under changing conditions. To initiate adaptation actions, decision makers need to understand the nature of these changes together with the capacity of the ecosystem and Inuit communities that rely on them to adapt (Smit and Wandel 2006). This involves drawing on all possible sources of information, including local, traditional and western scientific knowledge, to develop a comprehensive understanding of climate-induced changes and the associated ecological and human responses (Pearce et al. 2009, 2010, 2011, 2012, 2015). Thus, an inclusive holistic approach, that includes biophysical and human components, is needed to characterize changes in arctic marine ecosystems in a manner that is relevant to Inuit communities and decision-making (Tengo et al. 2014).

Inuit, scientists, and resource managers all have vested interests in the conservation and sustainable use of the arctic marine ecosystem (Robinson and Wallington 2012). The inclusion of all knowledge holders and users in developing research and management plans creates an enriched understanding of the changes occurring in arctic marine ecosystems and supports knowledge generation and sharing (Tengo et al. 2014). The team members assembled for this proposal have been at the forefront of marine ecosystem research in the Inuvialuit Settlement Region (ISR) over the past decade, and both together and separately, have worked collaboratively with Inuit communities to better understand environmental changes in arctic marine ecosystems to support adaptation decision-making, monitoring and policy (Loseto et al. 2006, 2008, 2015; Pearce et al. 2009, 2010, 2011, 2012, 2015; Desforges et al. 2013a,b ; Noel et al. 2014 ; Ostertag et al. 2014).

Indicators are being used across the Arctic at various scales, including local, regional and circumpolar, to monitor changes in the environment (National Oceanic and Atmospheric Association Arctic report card), biodiversity (e.g. Circumpolar Biodiversity Monitoring Program), and communities (Arctic Social Indicators, Arctic Human Development Report). Indicators can be used to characterize ecosystems in simpler terms, and provide a baseline from which to monitor change and inform management (Jackson et al. 2000). In recent years, there have been calls for research to improve the infusion of multiple sources of knowledge, traditional and western scientific, into real-world problem solving (World Social Science Report 2013). In addition, scientific and local observations of environmental change can be brought together to identify new avenues for further exploration, compare observations from different scales and discuss potential mechanisms that explain both sets of observations (Huntington et al., 2000). While the potential of this approach is acknowledged, there has been limited success in bringing diverse knowledge systems together in assessments to inform decision-making and policy (Danielson et al., 2014). Co-management of wildlife and other renewable resources was established under the Inuvialuit Final Agreement (INAC 1984), and continues at present with Inuvialuit and Department of Fisheries and Oceans co-managing marine resources. This process involves negotiation, deliberation, knowledge generation and joint-learning (Berkes 2009), and offers the opportunity to bring together complementary knowledge systems for sustainable ecosystem management (Tengo et al. 2014). The co-production of knowledge is an approach for connecting knowledge systems that engages mutual processes at all stages of knowledge generation, including the setting of goals, the generation of knowledge and the re-assessment of knowledge gaps and new questions (Tengo et al. 2014). Focusing on the process of knowledge co-production has been identified as an important element for improving power distribution among knowledge-holders, generating questions and enabling ecosystem assessments (Tengo et al. 2014).

Regional management bodies aim to include both Inuit and western scientific knowledge for ecosystem management in the ISR (e.g. Beluga management plan), but few have carried this out using principles of co-production. There is a need to conduct research to link biophysical and human elements of the marine ecosystem (i.e. ecological, social, economic) to identify indicators of change in Beaufort Sea. A "co-production" research framework would assist in the inclusion of diverse knowledge and perspectives in the development of user-specific monitoring objectives, and identification of appropriate indicators and ecosystem linkages to support adaptive co-management (Berkes 2009). Despite our current understanding of recent changes in arctic marine ecosystems, developing and monitoring ecosystem indicators that draw on both Inuit TEK and western science remains in its infancy.

ACTIVITIES

During 2015-2016 activities included community consultations, field research, data collection, data analysis, community meetings/workshops, engaging multiple stakeholders (community members, industry and management), manuscript submissions and presentations to both Inuvialuit communities and the national and international scientific communities. These activities occurred under the umbrella of two program themes of local and regional scale indicator development, including the identification, selection and validation using a co-production approach. In addition to activities listed below we held a pre-planning meeting with partners to confirm deliverables for 2015-16, secondly our team chaired the co-production session at the ArcticNet Annual Scientific Meeting in December 2015 in Vancouver, BC.

Local Scale Beluga Indicators: a) LEK/TEK indicator development, b) Western Science indicator development, c) co-production of beluga whale indicators

a) LEK/TEK Indicator Development

- **Community Consultation Meetings:** Researchers met with the Inuvialuit Game Council, Fisheries Joint Management Committee and Ulukhaktok Hunters and Trappers Committee (HTC) and presented the research, identified local research partners and methods for data collection (interviews). Community consultation took place in January and February 2016 in Paulatuk and Tuktoyaktuk to initiate student research on TEK about beluga and climate change.

- **Data collection:** Data collection occurred in Ulukhaktok, Tuktoyaktuk, Inuvik and Paulatuk. In Ulukhaktok, 30 in-depth interviews were completed about beluga behaviour, ecology, hunting technique, and muktuk preparation over a 6-week period. In Paulatuk, in-depth interviews about climate change and vulnerability, including the effects on beluga whale harvests were conducted with Inuit over a 6-week period. Beluga sightings (n = 119) and harvester observations (n = 33) were recorded in Darnley and Kugmallit Bays by community members from Inuvik, Tuktoyaktuk and Paulatuk.
- **Data analysis and synthesis:** Data verification with community experts (n = 28) identified by local HTCs in Paulatuk, Tuktoyaktuk and Inuvik in June 2015. Individual meetings with community experts are planned for February 2016 to select and evaluate local indicators, and identify TEK indicators for local beluga project (Ostertag et al., in prep). Review questions for Beluga Observation Application with community experts and HTC RPs are also underway for February 2016.

b) Western Science Indicator Development

- **Community Consultation meetings:** Researchers met with the Inuvialuit Game Council, Fisheries Joint Management Committee and Presidents Committee, and the Hunters and Trappers committees of Inuvik, Aklavik, Paulatuk, Tuktoyaktuk and Ulukhaktok. Here we presented our research plan to collected field data on beluga habitat, habitat use and beluga health related metrics. Health metrics included: morphometrics/condition, diet indicators, diseases, contaminants, hormone and vitamin levels.
- **Data Collection:** Beluga habitat characterization and use completed in Kugmallit Bay. Completion of seafloor bottom mapping and characterization. Deployment of moorings equipped with hydrophones, CTDs and turbidity at three locations. Beluga health sample analysis partnered with harvest monitoring program at three core locations: Hendrickson Island (Tuktoyaktuk harvest site), East Whitefish (Inuvik Harvest site), Darnley Bay (Paulatuk Harvest site).
- **Data analysis and synthesis:** Complete beluga habitat analysis for indicator selection at the Beaufort Coastal shelf scale (Hornby et al., in press). Analysis of Kugmallit Bay seafloor habitat completed, manuscript in preparation (Whalen et al., in prep). Beluga habitat use of Kugmallit Bay in phase one analysis of beluga vocalization in tandem with CTD and turbidity data. Beluga health indicator laboratory analyses underway, with three manuscripts in preparation and one in review (Choy et al., in review). Synthesize scientific understanding of beluga health and habitat use in the Beaufort (Feb 2016; Loseto et al., in prep).
- **Communication:** Presentations at ArcticNet Annual Scientific meeting, Northern Contaminants Program Scientific Results workshop and Society of Marine Mammology Biennial Conference: At ArcticNet, three oral presentations and one poster describing preliminary analysis of the Ulukhaktok interview data were presented, one presentation on local ecological indicators, one poster on the development of an online beluga observations application was presented, and two posters on the proposed research in Paulatuk and Tuktoyaktuk were presented.

c) Co-Production of Beluga whale indicators

- **Bridge local knowledge and science:** Beluga Summit – meeting to be held February 2016 in Inuvik to introduce local indicators to scientific community and identify how local indicators provide novel information for assessing and monitoring beluga.

» During our IGC/FJMC meetings in June in Ulukhaktok a spontaneous co-production meeting took place that brought together Inuvailiut Hunters (Inuvik, Aklavik, Tuktoyaktuk) with Ulukhaktomuit hunters to share knowledge of beluga hunting and muktuk/meat preparation.

- **Community/stakeholder consultation:** Presented approach and plan to Inuvialuit Game Council and Fisheries Joint Management Committee (x2). Develop framework on co-production process at the local scale for beluga. Beluga Summit Steering Committee (representatives from DFO (managers and scientists), IRC, NCP, IGC, FJMC) meetings held in September, October, December 2015 and January 2016.
- **Planning for data collection:** Held meetings with all ISR community delegates to discuss best approach for sharing knowledge for co-production.
- **Communication with northern organizations:** Results from the beluga research program were presented (both western scientific and local indicator components) to the Fisheries Joint Management Committee, Inuvialuit Game Council, Inuvialuit Inupiat Beluga Whale Commission, and local Hunters and Trappers Committees.
- **Science communications:** Presentations at ArcticNet ASM, Northern Contaminants Program Scientific Results workshop and Society of Marine Mammology (SMM) Biennial Conference. At ArcticNet, two presentations on the co-production of knowledge on beluga diet and habitat use were presented. At the NCP results workshop, our team presented on a panel from an Inuvialuit and academic perspective about beluga research in the ISR in addition to one poster on local ecological indicators and bridging knowledge. At the SMM there was one presentation on bridging knowledge on beluga health and habitat use.

Regional Scale Marine Indicators: a) Management objectives assessment, b) Ecological indicator assessment

a) Management objectives assessment

- **Community consultation meetings:** Researchers met with the Fisheries Joint Management Committee annual meeting in Winnipeg (Jan 2015), at the Inuvialuit Game Council meeting in Ulukhaktok (June 2015), and with separate presentations to the Inuvik and Tuktoyaktuk Hunters and Trappers Committees (HTC) (June 2015). Informal consultations also occurred with the Tuktoyaktuk and Ulukhaktok Community Corporations (June 2014). Presentation with the HTCs co-occurred with local indicators workshops. During these presentations, community members and co-management boards were provided an overview to the three year regional program, as well as year one research plans.
- **Data collection/consultation:** A comprehensive literature review was combined with co-management agency consultation to identify the long-term marine resource objectives for each agency. Over 3000 initial documents were initially identified for the 14 co-management agencies with marine resource responsibility. These were reviewed in detail and reduced to 77 core documents with 398 regional management objectives.
- **Data analysis and synthesis:** Two analyses completed; categorical assessment into five major categories (ecological, cultural, social, cultural, governance); and a level assessment to quantify how broad or narrow each objective was for indicator identification with targets (Grandmaison et al., in prep).

- **Stakeholder prioritization:** Prioritization of objectives occurred during the Beaufort Sea partnership (BSP) annual meeting (Inuvik-October 2015), whereby stakeholders (management, science, industry, community members) evaluated and prioritized core objectives across five themes (ecological, economic, social, cultural, governance). Four working groups (Beaufort Sea Governance, Traditional Knowledge, Ecological and Socio-economic), provided input on the priorities under each category.
- **Communication:** Results were presented during the Beaufort Sea Partnership meeting (Inuvik-Oct 2015), at the ArcticNet annual Conference (Vancouver-Dec 2015) and at the FJMC annual meeting (Winnipeg-Jan 2016).

b) Ecological indicator assessment

- **Community consultation meetings:** Researchers met with the Inuvialuit Game Council, Fisheries Joint Management Committee, Aklavik Hunters and Trappers committee and the community audience at the BREA wrap meeting in Inuvik. Here we presented how we will use diet biotracers (stable isotopes, fatty acids) to examine linkages across different levels of the food web along with other approaches and collaborators, with a focus case study at Shingle Point (Aklavik fishing site). As recommended by the community of Aklavik a TEK component was added to the Shingle point program.
- **Data collection:** The fish case study at Shingle point included fish collected over three years across 16 species. This will be combined with biomarkers for other levels of the food web and other approaches to provide a better understanding of the food web and key species to be used as indicators.
- **Data analysis and synthesis:** We completed the Shingle Point diet biotracer analysis among 16 species (Brewster et al., in prep). Use of Ecoapth with Ecosim (EwE) food web model to identify indicator species as a complementary approach to biomarkers (Hoover et al. in prep). This model of the Beaufort Sea Shelf identifies changed to the food web from 1970-2012 with all species represented, highlighting unique species in the system. Integration of Biomarkers with Ecopath with Ecosim food web models to assess complementary approaches in identifying indicator species across the food web. This highlights strengths and weaknesses in each approach.
- **Communication:** Results were presented to Fisheries Joint Management Committee in Jan 2016 and will be shared with communities this fiscal year.

RESULTS

We had an extremely productive first year of our program with fruitful community meetings, early publications and the analysis of new data that will facilitate the co-production of indicators for monitoring. Due to the timing of the annual report we are unable to share our co-production results from our Beluga Summit that will foster the dialogue between community members, scientists and managers.

Local Scale Beluga Indicators:

a) LEK/TEK Indicator Development

Characterization of beluga health from an Inuvialuit perspective included observations made during beluga harvesting, butchering and preparation (Ostertag et al., in prep). In general, harvested belugas were selected by hunters if they appeared healthy and were the desired size; thus, the whales that were butchered between 2013 and 2015 by community members from Tuktoyaktuk, Paulatuk and Inuvik were in good health. Interview responses provided additional information about the characteristics of sick or unhealthy whales harvested in the past. Due to the overall harvester selection of healthy whales, interview data were combined with the responses from harvester questionnaires, to characterize healthy, less healthy and sick whales. In general, beluga health was determined during harvesting based on the appearance and behaviour of the whales; during butchering, the quantity and quality of skin and blubber and muscle, and the appearance of internal organs; and, during preparation, appearance of the muktuk, blubber and muscle.

In the next phase, community experts will identify local indicators of beluga health and suggest the most appropriate methods for monitoring these indicators. The potential for these indicators to support beluga monitoring will be evaluated scientifically based on the following criteria:

1. Can the observation be recorded by harvesters, beluga monitors and/or community members?
2. Is this observation considered to be important by community members based on consensual informant responses or key informant responses?
3. Can this observation be recorded with existing scientific studies; and
4. Can this observation be quantified and/or compared between years and/or communities?

General areas of beluga sightings and habitat use were collected between 2013 and 2015 (Figure 1), and verified in June 2015 during community focus groups and will be updated to include additional feedback from community experts (Feb 2016). Inuvialuit knowledge of beluga calving areas, potential nursery areas, feeding areas and travel routes/times in the areas surrounding the communities of Tuktoyaktuk, Paulatuk and Ulukhaktok, and harvest sites (East Whitefish, Kendall Island and Hendrickson Island) provides unique and significant information to support the monitoring of beluga habitat use in these coastal areas (Ostertag et al., in prep). The interpretation of annual beluga sighting data will likely require further interviews with community participants, to ensure that it is grounded in the knowledge held by Inuvialuit TEK holders. Interviews with community experts in

Figure 1. Locations where beluga observations were recorded between 2013 and 2015 in the ISR. Observations about harvested and sighted whales were recorded by community members using survey forms, semi-structured questionnaires or semi-structured interviews based on the whales harvested in these locations and years.

February will be used to identify how beluga sightings should be collected, verified and interpreted in the ISR.

Interview data collected in Ulukhaktok is being analyzed and together with participant observation of beluga hunting by Ulukhaktomuit hunters in 2014 will form the basis of two papers: (i) Inuit knowledge of beluga whale behavior and ecology under changing climatic conditions and (ii) Inuit knowledge of beluga hunting techniques and food preparation. New data on beluga whale behaviour and ecology, hunting techniques and food preparation will be collected with experienced Inuvialuit hunters in the Mackenzie Delta in summer 2016. These data sets represent knowledge from a population for whom beluga is a new species important for subsistence and a population with a long history of hunting and eating beluga.

b) Western Science Indicator Development

Health and habitat related measurement in support of western science indicators were completed in 2015. For habitat use of the Beaufort Sea shelf, beluga locations from spring (2012-2103) and late-summer (2007-2009) aerial surveys were analyzed with environmental variables to understand seasonal movement and habitat selection. The results of this study suggest that the Shallow Bay (and ice edge), where increased freshwater was present, may provide key habitat variables for beluga before break-up. In the late-summer, high-use areas in the offshore Beaufort Sea were similar to regions previously identified as having increased upwelling and large aggregations of Arctic cod.

For our fine scale habitat analyses in Kugmallit Bay interpolation of sonar (water depth), sidescan (seabed roughness) and seabed sediment type a total of five unique potential habitats were determined. New data in 2015 also showed the presence of gravel beds running parallel to the shoreline, which are known to be a preferred beluga habitat for moulting (Whalen et al., in prep). Although the seabed appears to remain stable throughout the season, preliminary results show dramatic changes in oceanographic conditions that unlike the seabed could influence beluga occurrence and mobility within the bay. Most of the time the area is dominated by the fresh water outflow from the Mackenzie River, except during NW storms when the area is inundated with colder and saltier water. Preliminary results based on new field data acquired from hydrophones placed strategically on the seabed in 2015 show that beluga whales respond to these conditions by avoiding or leaving the areas with cold and salty waters.

Beluga health indicator development continues at multiple levels with measurements supporting indicator development for condition, diet indicators, diseases, contaminants, hormone and vitamin levels (e.g. Loseto et al., 2015, Choy et al., in review).

c) Co-Production of Beluga whale indicators

As our first step toward the co-production of beluga whale indicators we are holding a regional communication meeting in Inuvik during the week of Feb 23rd. In anticipation of the meeting a steering committee was developed with members from the FJMC, IGC, IRC and DFO. The team met monthly to develop a plan and framework to support the co-production knowledge on beluga whales. Currently we have completed our first round of preparation meetings with the community delegates. We look forward to reporting on outcomes from the meeting.

Regional Scale:

Results from the systematic literature review identified 1833 documents across 14 co-management agencies. Ultimately 77 documents were retained, as they were relevant to marine resource management within the ISR, with 398 objectives being used for further analysis (Figure 2).

Categorization of objectives by co-management agency into five main categories (Ecological, Social Economic, Cultural, or Governance) reveals most agencies provide a balanced perspective of objectives (Figure 3, from Grandmaison et al. in prep). This indicates that even though different agencies tend to have a specific focus (i.e. ecological), they consider management responsibilities in the context of the larger perspective (what are the social or economic impacts of managing the ecosystem). This analysis follows in line with the Integrated Oceans Management Plan (IOMP), in that management agencies manage in an interdisciplinary context, and consider the greater ecosystem (including humans) when managing.

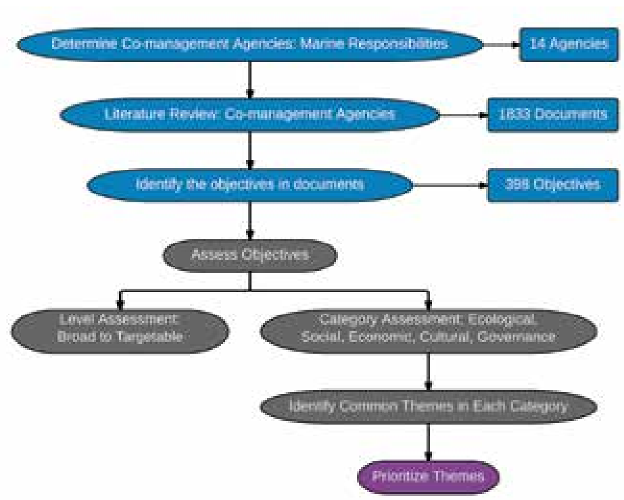

Figure 2. Overview of documents and analyses preformed in order to identify common themes for co-management objectives across the ISR.

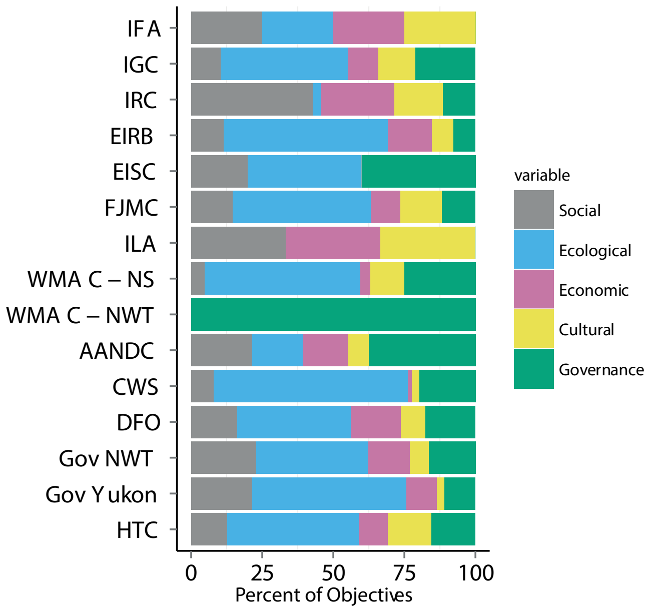

Figure 3. Categorization of co-management objectives. Co-management agencies: Inuvialuit Game Council (IGC), Inuvialuit Regional Corporation (IRC), Environmental Impact Review Board (EIRB), Environmental Impact Steering Committee (EISC), Fisheries Joint Management Committee (FJMC), Inuvialuit Land Administration (ILA), Wildlife Management Advisory Council- North Slope (WMAC-NS) and Northwest Territories (WMAC-NWT), Aboriginal Affairs and Northern Development (AANDC), Canadian Wildlife Service (CWS), Fisheries and Oceans Canada (DFO), Governments of Yukon (Gov Yukon) and NWT (Gov NWT), Hunters and Trappers Committees (HTC), and the governing Inuvialuit Final Agreement (IFA). For each agency the condensed objectives were categorized based on their main associations, as they related to the five main categories. Results are presented as percent contribution by category to identify large scale patterns across agencies.

Analyses reveal less than 5% of all objectives are targetable (level 1: L1), meaning they lack a targetable indicator and measurement (Figure 4). Level 2 objectives have some specificity in what they intend to measure, but lack a definitive or targetable goal; meaning level 1 and 2 objectives are ideal for monitoring programs because they can be measured. Level 2 objectives require some clarification, while level 1 objectives were clear in what they intend to measure or target. Higher level objectives (Levels 3 and 4) are more broad, and require some guidance or "unpacking" in order to be used to direct monitoring programs. These make up 67% of all co-management objectives, with the broadest category (level 4: considered immeasurable) contributing 20% to total objectives. This analysis reveals the need for clear, targetable objectives when setting management targets in monitoring.

From the categorization analysis, we were able to find common themes (3-6) under each of the five categories. These were presented at the BSP meeting in October where regional stakeholders were asked to indicate their personal preference for priorities. Preliminary results indicate most stakeholders felt the common themes developed by the research team captured the needs of management in the region, and were able to identify high-priority themes. Final results of the prioritization are expected in 2016.

Knowledge co-production at the regional level presents a different process than the local level. At the regional level stakeholders are made up of co-management agencies, industry, management (local, regional, national), and community members. Because much of the work relating to regional objectives and indicators has been completed by individual agencies, consultations served as the initial step in gathering knowledge. Consultations with stakeholders at the annual BSP meeting served as the next major step in the co-production process by including perspectives from regional stakeholders. Further assessments of the differences in knowledge co-production will be documented to contribute to the growing body of literature and provide perspective as to local vs regional differences.

Ecosystem Level Indicators

Case study results from the Shingle Point fish assessment revealed the diet biomarkers (stable isotopes and fatty acids) distinguished several key fish groups from which niche assessments were completed. Among each of the fish groups a niche assessment

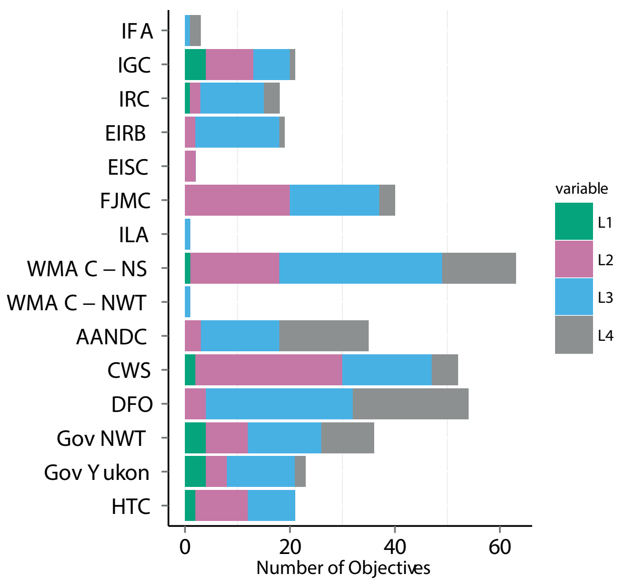

Figure 4. Level analysis of objectives for co-management agencies and founding document (IFA). See Figure 3 caption for full agency names. Total number of objectives are broken down by each agency as they relate to each level: Level 1 (L1) objectives are specific with measurable targets, Level 2 (L2) objectives are specific without measurable targets, Level 3 (L3) objectives are broad with some direction for unpacking, and Level 4 (L4) are broad (not measurable) with no direction for unpacking.

was performed among species to evaluate feeding and habitat overlap to assist with the selection of key fish for long term ecosystem monitoring (e.g. Figure 5).

Results of the Beaufort Sea Shelf ecosystem model (EwE) identify key species within the food web to be used as potential indicator species (Hoover 2013). The EwE model and biomarker data have recently been combined in order to validate both approaches, and highlight key species as potential indicators (Hoover et al., in prep).

DISCUSSION

Local Scale: LEK/TEK indicator development

Beluga health is characterized from an Inuvialuit perspective in the context of beluga as an important food resource. Therefore, harvested belugas are typically healthy and their health is defined largely by the quantity and quality of the animal's muktuk, blubber and muscle, which are the primary organs utilized today for food. Examples of how the scientific community monitors beluga health includes the study of infectious disease, lesions/neoplasms/tumours, reproductive success/complications, blubber thickness, growth rates/age at growth, indicators of stress, exposure to contaminants and toxicological endpoints (Harwood et al., 2014; Desforges et al., 2013a,b; Lair et al., 2016; Loseto et al., 2015; Nielsen et al., 2001; Noel et al., 2014; Ostertag et al., 2013, 2014; Pleskach et al., in prep). Scientific studies often require scientific expertise onsite to collect samples or conduct a thorough necropsy of dead animals, which would be logistically and economically unfeasible for all harvested whales. The study of beluga health from an Inuvialuit perspective adds value to beluga monitoring in part by providing a long-term perspective on beluga health based on generations of harvesting activities (McGhee, 1998) and by providing in-depth knowledge about the overall health of each harvested whale.

Local observations and TEK about beluga habitat use reflect observations made during the everyday activities of community members in addition to specific beluga harvesting activities. In the Mackenzie Delta and Darnley Bay, the Inuvialuit residing in coastal communities or camping at coastal harvest camps observe beluga throughout the summer and fall (June to November) while travelling, fishing, spending time outside and harvesting beluga. The observations made by Inuvialuit TEK holders in this area reflect a long history of observing beluga and inter-generational transmission of knowledge about beluga habitat use. Beluga habitat use in the Inuvialuit Settlement Region has been recorded and characterized by scientists by recording vocalizations (Simard et al., 2014), aerial surveys (Hornby et al., 2014, in press; Harwood et al., 2014) satellite tagging (Hauser et al., 2014; Richard et al., 1998) and the analysis of relationships between environmental variables and habitat use (Simard et al., 2014; Hornby et al., 2014, in press). Beluga distributions and subsequent habitat selection may already be changing over space and time. By incorporating aerial survey methods with habitat analysis, the relationships between beluga and the habitats they occupy can be examined at a finer scale. These habitat-relationships enhance our baseline from which to study the effects of climate change and inform future monitoring program.

Observations made by the Inuvialuit have the potential to expand the spatial and temporal scale of recorded beluga habitat use. In addition, TEK provides a historical context to present day beluga sightings and changes being observed in the ISR. Traditional Ecological Knowledge also supports the development of research questions and methods in response to environmental changes occurring in the ISR.

The Beluga Summit will offer the first venue of its kind to bring together knowledge holders from different expertise and knowledge centers together in one northern location to share knowledge. Here knowledge holders of beluga TEK/LEK and beluga western science knowledge will share knowledge on beluga whales with one another. In preparation for the next step, 'co-production' both the western science and TEK/LEK knowledge holders have been consulted on how to foster dialogue and the 'co-production' of knowledge in support of decision making. The framework is in development and central to the framework will be to identify gaps and set forward direction for future research in support of decision-making and the long term viability of this beluga population.

Regional Scale: Management objectives assessment

By completing an assessment of existing objectives, the research team was able to provide an independent assessment to the Integrated Oceans Management Plan (IOMP), a regional overarching management plan, which intends to "review achievement of objectives and strategies" every five years (Beaufort Sea Partnership 2009). Our independent assessment highlights the success of the IOMP in outlining diverse objectives, across the five categories assessed. However, higher level management and monitoring plans tend to have more broad non-targetable objectives, suggesting a trade-off between diversity and specificity.

From the full list of objectives, high priority themes were identified from regional stakeholders. These are intended to guide research activities in upcoming years for indicator selection. These priorities will feed back into regional co-management agencies and serve as a reference for agencies to compare their individual objectives and priorities against the larger regional perspective.

Regional Scale: Ecological indicator evaluation

In order to select meaningful indicators for monitoring programs, clear objectives are needed to direct management (Rice and Rochet 2005). Based on our assessment of objectives, there is a disproportionate amount of broad non-measurable objectives for marine monitoring, which makes future indicator selection potentially difficult. Nearly 2/3 of regional objectives are currently non-measurable (without further work), meaning changes to initial objective have the potential to streamline monitoring programs and make them more focused on priorities, rather than attempting to capture all possible changes in the system. Because this project is occurring in real-time along with the development of MPA (Marine Protected Area) monitoring goals, there is the potential to work alongside DFO partners to develop more tangible goals for future programs. With respect to the remaining co-management agencies, the research team hopes to provide recommendations regarding objectives to support future updates to monitoring programs regarding indicators.

Work starting in Year 1 has initiated collection of regional ecological indicators, work that is expected to continue throughout the program. As indicator selection can be data intensive, we aim to integrate data from as many sources as possible to feed into a common database for use during this project and as a legacy. Results and outcomes from the Shingle Point case study provided guidance on key indicator fish for selection of long term monitoring as well as the identification of which 'diet biomarkers' will support a long term monitoring program of fish diet and habitat use based on sensitivities (Brewster et al., in prep). Preliminary results from biomarker analysis compared with EwE models for the Beaufort Sea food web suggests a good understanding of the overall food web. While many projects will feed data into the larger database on indicators, individual contributions are still an important and necessary component.

CONCLUSION

The Arctic marine ecosystem is undergoing rapid change under new climatic conditions with implications for marine biota and the human communities who depend on them for their livelihoods. There is a vested interest among Inuvialuit, Inuit and other decision makers to monitor these changes to inform management practices. Indicators are useful for characterizing ecosystems in measurable terms that can be monitored for management purposes but objectives and targets must be clearly defined for setting management priorities in order for indicators to be relevant. Moreover, Inuit have a highly detailed and holistic understanding of the marine ecosystem, which taken together with western scientific understanding can develop more robust and accurate indicators and monitoring programs. This research program seeks to bridge Inuvialuit knowledge and western scientific knowledge through the co-production at two scales, one at the local scale focused on knowledge related to beluga whales and two at the regional scale to identify relevant indicators to monitor and measure changes in the Beaufort Sea ecosystem.

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ArcticNet
Pavillon Alexandre-Vachon
1045, avenue de la Médecine, Room 4081
Université Laval
Quebec City, Quebec G1V 0A6
T: (418) 656-5830
F: (418) 656-2334

ᐅᑭᐅᖅᑕᖅᑐᖏᒃ ᑐᑭᓯᓂᐊᖃᑎᒌᑦ
Pavillon Alexandre-Vachon
1045, avenue de la Médecine, Room 4081
Université Laval
Quebec City, Quebec G1V 0A6
ᐅᖃᓗᑎ: (418) 656-5830
ᓱᒃᑲᔪᒃᑯᑦ: (418) 656-2334

ArcticNet
Pavillon Alexandre-Vachon
1045, avenue de la Médecine, local 4081
Université Laval
Québec (Québec) G1V 0A6
Tél. : (418) 656-5830
Téléc. : (418) 656-2334

www.arcticnet.ulaval.ca