ArcticNet

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Impacts of Environmental Change in the Canadian Coastal Arctic

A Compendium of Research Conducted during ArcticNet Phase III (2014–15)

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Editorial Team:
Mickaël Lemay, Ashley Gaden and Carl Barrette.

ArcticNet is hosted at Université Laval, Quebec City, Quebec, Canada.

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

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

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

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ᐅᑯᐊ ᐱᑐᒃᓯᒪᕙᑦ ᐱᐅᓛᑦ ᑲᓇᑕᒥ ᐊᔾᔨᐅᙱᑑᔪᒥᒃ ᐱᓇᓱᐊᖅᑎᕈᓘᑦ ᐊᕙᑖᓂᑦ ᐃᓕᓐᓂᐊᕐᕕᒃᔪᐊᓂ, ᐱᓇᓱᐊᖅᑐᓕᕆᓂᖅ ᑲᓇᑕ, ᒐᕙᒪᒃᑯᑦ ᐊᒻᒪᓗ ᑮᓇᐅᔭᓕᐅᕋᓱᐊᕋᑎᒃ ᐊᐅᓚᑦᓯᔨᐅᔪᑦ ᑐᕌᖅᑐᑦ ᑐᓄᑎᒍᓐᓇᖅᑐᒍ ᑲᓇᑕᒥᐅᑦ ᖃᐅᔨᓴᖅᓂᙳᑦ ᐊᒻᒪ ᓇᙳᒥᓂᖃᖅᑐᓕᕆᓂᖅ ᐱᓕᕆᐊᓇᑦᓯᐊᖅᑐᑦ ᑕᒪᑐᒎᓚ ᒪᑭᑕᓇᓱᐊᕐᓂᕐᒧᑦ ᐊᒻᒪᓗ ᐃᓅᓯᕐᒥ ᐃᑲᔪᕐᑎᓂᐊᖅᑐᓄᑦ ᑕᒪᐃᓐᓄᑦ ᑲᓇᑕᒥᐅᓄᑦ. ᑕᐃᒪᓗ ᐃᓗᓪᓕᕆᓗᐋᖅᑕᕙ ᐃᓚᖓ ᒐᕙᒪᖅᑯᑦ ᓄᑖᓂᒃ ᐱᕐᕋᓪᓚᒍᑎᓕᕆᓂᖅ ᐋᕐᒃᓯᒪᐅᑎᙱᑦ, ᐅᑯᐊ ᑲᓇᑕᓕᒫᑦ, ᐊᒥᓱᑦ ᐃᓂᖅᑎᕆᔪᓐᓇᖅᑐᑦ ᐊᒻᒪᓗ ᐊᒥᓱᑦ ᖃᓄᐃᓐᓇᖅ ᐱᓕᕆᔪᓐᓇᖅᑕᓕᑦ ᑲᑎᙵᔪᑦ ᐱᐅᓂᕐᕚᙳᔪᒥᒃ ᖃᐅᔨᓴᐃᓂᕐᒥᒃ ᐱᓇᓱᐊᖅᑐᓕᕆᓂᕐᒥ ᖃᐅᔨᓴᖅᑕᐅᓕᕈᓐᓇᖅᑐᓂᒃ ᐊᒻᒪᓗ ᐋᕿᒃᓯᒪᐅᑎᙱᑦ ᖃᑭᓕᐊᕈᑎᕆᔪᓐᓇᖅᑐᓂᒃ.

ᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖅᑎᕆᑦ ᐱᑐᒃᓯᒪᖅᑎᕆᔭᙱᑦ ᑖᒃᑯᓐᓇᙵᑦ ᑐᑭᓯᒐᓱᐊᖅᑎᕇᑦ ᐱᑐᒃᓯᒪᓂᒃᑯᑦ ᐱᐅᓈᑦ ᑲᓇᑕᒥ ᑎᒥᙳᖅᑎᑕᐅᓯᒪᔪᑦ ᑮᓇᐅᔭᓕᐅᖅᑎᐅᓚᐅᓯᐊᕐᕕᒃ ᑯᐊᐳᓴ ᐊᑖᒍᑦ ᐊᑎᖃᖅᖢᑎᒃ "ᐅᑭᐅᖅᑕᖅᑐᒥᒃ ᑐᑭᓯᓂᐊᖅᑎᕇᑦ ᑎᒥᖓ" ᑕᐃᑲᓂ ᑎᓯᐱᓇ 2003.

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

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

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

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

Canada

Coming together in the study of a changing Canadian Arctic.

ᐊᐅᓪᓚᖃᑎᒌᒃᓯᒪᔪᑦ ᐃᓕᑦᑎᓇᓱᖃᑎᒌᒃᑐᒡᓗᑎᒃ ᐊᓯᑦᔨᕐᐸᓪᓕᐊᓂᖓᓂᒃ ᑲᓇᑕᐅᑉ ᐅᑭᐅᖅᑕᖅᑐᖓ.

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

TABLE OF CONTENTS

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 final year of phase III (2014-2015) 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

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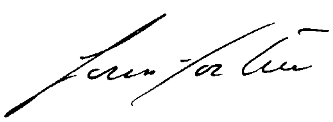
ᐅᓇ ᐅᑭᐅᖅᑕᖅᑐᖅ ᓄᓇᖓ ᓄᓇᕐᔪᐊᒥ ᐊᒃᑐᖅᑕᐅᖄᕐᓂᐊᖅᑐᖅ ᐊᒻᒪᓗ ᐊᖏᓛᖑᔪᐊᒥᒃ ᓱᑯᑕᐅᓗᓂ ᑕᒪᑐ-
ᒪᖓᑦ ᓂᒋᐊᓂᒐᖅᑐᓂᑦ ᐅᖅᑰᓯᕙᓪᓕᐊᓂᖓᓄᑦ ᓄᓇᕐᔪᐊᑦ. ᐅᓄᖅᑐᑦ ᑕᒻᔭᐅᓕᖅᑐᑦ ᖃᐅᔨᑦᑎᕙᑦ ᐅᑭᐅ-
ᖅᑕᖅᑐᖅ ᐅᕐᑰᓯᓂᖓᓄᑦ ᖃᐅᔨᔾᔪᑎᖃᖅᖢᑎᒃ ᓯᓚᐅᑉ ᖃᓄᐃᓐᓂᖓᓂᒃ ᓴᓇᕐᕈᑕᐅᔪᓂᒃ ᓇ, ᓇᐃᖅᑐᖅ ᑕᑯᔭ
ᐅᔪᖅ ᓄᓇᑐᐃᓐᓇᒥ, ᑕᕆᐅᕐᒥ ᐊᒻᒪᓗ ᓄᓇᕐᔪᐊ ᓯᓚᑖᓂ. ᓇᐃᓈᖅᖢᒍ ᐅᖃᕈᓐᓇᖅᑐᒍᑦ ᐅᑭᐅᖅᑕᖅᑐᖅ
ᓯᓚᖓᑕ ᐊᕙᑎᖓᑕ ᐊᓯᑦᔨᕐᓂᖓ ᐊᒃᑐᖅᑕᐅᓂᖓᓂᒃ ᓱᕐᑯᐃᖅᑕᐅᓇᓱᒃᓯᒪᔪᓂᑦ 2004, ᐊᒥᓱᑦ ᐊᔾᔨᒌᙱᑦᑐᑦ
ᓯᓚᓐᓂᐊᖅᑐᑦ, ᐃᓅᓯᓕᕆᓂᕐᒥᒃ ᑮᓇᐅᔭᑎᒍᑦ ᐱᕙᓪᓕᐊᓂᖅ ᐊᒻᒪᓗ ᓄᓇᖏᓐᓄᑦ ᑲᕙᒪᓕᕆᓂᖅ ᑕᒻᔭ ᐱᓕᕆᔭ
ᐅᔪᑦ ᐅᑭᐅᖅᑕᖅᑐᒥ ᑕᐃᒪᓗ ᐊᓯᑦᑏᓂᐊᖅᑐᖅ ᑭᓱᖑᒍᕐᓗᓂ ᐅᑎᕈᓐᓇᕐᓂᐊᙱᑦᑐᖅ ᐅᑭᐅᖅᑕᖅᑐᒥ ᑕᐃᒪᓐᓇ-
ᐅᖏᓐᓇᐅᔭᓕᕐᓂᐊᖅᑐᑦ. ᐅᑭᐅᖅᑕᖅᑐᒥ ᑐᑭᓯᓐᓂᐊᖃᑎᒌᑦ ᓄᐊᑎᕆᔪᑦ ᖃᐅᔨᒪᔭᐅᔪᓂᒃ ᐊᒻᒪᓗ ᓱᕐᑯᕈᐃᖅᑕ-
ᐅᓯᒪᔪᓂᒃ ᑭᖕᖒᒪᒋᔭᐅᓯᒪᔪᓂᒃ ᐋᕿᒃᓯᓂᐊᕐᓗᑎᒃ ᓱᖏᐅᑎᑦᑎᔾᔪᑎᒃᓴᐃᑦ ᐊᒻᒪᓗ ᐊᑐᐊᒐᐃᑦ ᐅᑯᐊ
ᐃᑲᔪᕐᓂᐊᖅᑐᖅ ᐅᑭᐅᖅᑕᖅᑐᒥᐅᓂᒃ ᐊᒻᒪᓗ ᑲᒻᐸᓂᐅᔪᓂᒃ ᐱᓂᒃᓴᐸᕇᖅᓯᒪᓗᑎᒃ ᐊᒃᑐᖅᑕᐅᓂᖓᕐᓂᖓᓄᑦ
ᐊᕙᑎᖓᑦ ᐊᒻᒪᓗ ᐃᓅᓯᖏᑦ ᐊᓯᑦᔨᕐᓗᑎᒃ ᓯᒃᔭᖏᑦ ᑲᓇᑕᐅᑉ ᐅᑭᐅᖅᑕᖅᑐᐊᓂ. ᐅᓇ ᑕᐅᑦᑐᕆᔭᕗᑦ ᓴᓇᓗᒍ
ᓯᕗᓂᒃᓴᕗᑦ, ᖁᔭᓐᓇᒦᒃ ᑕᒻᔭᐅᖕᒪᑦ ᑐᓴᐅᒪᖃᑎᒌᖕᓂᖅ ᖃᐅᔨᒪᖃᑎᒌᖕᓂᖅ, ᒥᐊᓂᕆᓂᖅ, ᐋᕿᒃᓱᐃᓂᖅ
ᐊᒻᒪᓗ ᐃᓗᓪᓕᖅᓱᐃᓂᖅ, ᖃᐅᔨᓴᖅᑎᒻᒪᕇᑦ ᐊᒻᒪᓗ ᐅᑭᐅᖅᑕᖅᑐᒥᐅᑦ ᑲᑎᓯᒪᔭᖏᓐᓂᑦ ᐱᓕᕆᑦᑎᐊᖅᓗᒋᑦ

ᐃᓕᓴᐃᔨᒪᓇᒃ ᓗᐃ ᕗᐊᑦᓯᔭᐃ, ᖃᐅᔨᓴᕐᓂᕐᒥᒃ ᑐᑭᒧᐊᒃᑎᑦᓯᔨ ᐅᑭᐅᖅᑕᖅᑐᕐᒥᒃ ᑐᑭᓯᓂᐊᖅᑎᕐᒃᑯᓐᓂ



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 dernière année (2014-2015) des projets de recherche de la phase III d'ArcticNet. 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 (2014-15) presents research progress of the final year of Phase III ArcticNet projects, which ran from 1 April 2014 to 31 March 2015. Thirty-three projects were organized under five complementary research themes of Phase III: 1) Marine systems (8 projects); 2) Terrestrial systems (9 projects); 3) Inuit health, education and adaptation (10 projects); 4) Northern policy and development (4 projects); and 5) Knowledge transfer (2 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.

2014-2015

ArcticNet: Canada's Premier Northern Research Network

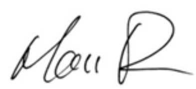
Since its inception in 2004, the ArcticNet Network of Centres of Excellence (NCE) has met the five criteria of the NCE program with increasing success: excellence of the research; training of the next generation of Arctic professionals; networking and partnerships; knowledge exchange and exploitation; and network management. The national and international reputation of the Network has grown steadily and our approach to knowledge mobilization through the Integrated Regional Impact Study framework has been emulated by the Arctic Council's Adaptation Actions for a Changing Arctic for the downscaling of its own circumpolar assessments of the ongoing transformation of the Arctic. Canada is now leading the modern exploration of the Arctic and the global quest to understand the fate of this last frontier and its communities under the triple pressure of climate change, development, and modernization.

As we enter the fourth and last phase of NCE funding, the Network is moving forward with an exciting new core program of 41 projects selected from no less than 86 submissions to its 2014 Call for Proposals. The Phase IV (2015-2018) program comprises 19 projects that build on Phase III research and 22 projects, or 54%, that are new to the Network. In addition, ArcticNet will welcome 69 new Network Investigators, equivalent to 56% of the total. In addition to this core NCE-funded program, several other impressive initiatives and activities conducted during 2014-2015 attest to the vigour of the Network. Among these, are the successful Amundsen application to the Canada Foundation for Innovation Major Science Initiatives Special Competition; the organization of the international Arctic Change 2014 conference and the Arctic Inspiration Prize Awards Ceremony; the evaluation, with flying colours, of the Schools on Board program; the initiation of the ArcticNet Fieldwork Safety Training Fund; the signing of an agreement with France's Centre national de la recherche scientifique for the sharing of Arctic expertise; the Northern Housing Forum; the International Symposium on Northern Development; Amundsen and ArcticNet research making the front page of The Globe and Mail; the participation of ArcticNet management in numerous international Arctic forums; and the welcoming of France's President Hollande and Quebec's Premier Couillard by ArcticNet and the Unité Mixte Internationale Takuvik.

But many other initiatives are in the making, and this flurry of exciting activities augmenting the core research program of ArcticNet in 2014-2015 is the harbinger of a plethora of outstanding new endeavours for Phase IV. Among many items, the international Green Edge program in Baffin Bay; the University of Manitoba-led Churchill Marine Observatory; the ArcticNet contribution to Polar Knowledge Canada and the Canadian High Arctic Research Station;

new research projects with The W. Garfield Weston Foundation; the Institut nordique du Québec; and, most importantly, the Sentinel North mega program recently funded by the Canada First Excellence Research Fund. ArcticNet continues to support world-class Arctic science and collaboration as Canada's premier northern research network.

Louis Fortier	Martin Fortier
Scientific Director	Executive Director



SECTION I. MARINE SYSTEMS

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

SEA ICE, CLIMATE CHANGE AND THE MARINE ECOSYSTEM

Project Leader

David G. Barber (University of Manitoba)

Network Investigators

Simon Prinsenberg (University of Manitoba)
John Yackel (University of Calgary)

Collaborators

Jens Ehn (University of Manitoba)
Steven Ferguson (University of Manitoba)
Louis Fortier (Université Laval)
Ryan Galley (University of Manitoba)
Michel Gosselin (Université du Québec à Rimouski)
Yves Gratton (Institut national de la recherche scientifique - Eau, Terre et Environnement)
David Holland (Courant Institute of Mathematical Sciences)
John Iacozza (University of Manitoba)
CJ (Christopher John) Mundy (Université du Québec à Rimouski)
Tim N. Papakyriakou (University of Manitoba)
Ingrid Peterson (Fisheries and Oceans Canada - Bedford Institute of Oceanography)
Soren Rysgaard (University of Manitoba)
Randall Scharien (University of Calgary)
Duane Smith (Inuit Circumpolar Council (Canada))
Gary A. Stern (University of Manitoba)
Kevin Sydor (Manitoba Hydro)
Jean-Eric Tremblay (Université Laval)

HQP

Karley Campbell, Doctoral Student (University of Manitoba)
Ice algal blooms in Resolute Passage
Nariman Firoozy, Doctoral Student (University of Manitoba)
Sea-ice inverse scattering
Mark Christopher Fuller, Doctoral Student (Circumpolar Flaw Lead (CFL) System Study)
Monitoring Snow Cover Characteristics in a Discontinuous Snow Covered Region using Active Polarimetric Microwave Remote Sensing
J.V. Gill, Doctoral Student (University of Calgary)
Poalrimetric Microwave Investigation of Snow Covered Sea Ice
Mukesh Gupta, Doctoral Student (University of Manitoba)
Role of surface roughness in moderating ocean-sea ice-atmosphere processes within the Marginal Ice Zone
Satwant Kaur, Doctoral Student (University of Manitoba)
Alexander Komarov, Doctoral Student (University of Manitoba)
Remote sensing methods of tracking sea ice
Jack Landy, Doctoral Student (University of Manitoba)
Sea ice surface morphology
Mallik Mahmud, Doctoral Student (University of Calgary)
High resolution estimates of sea ice melt onset timing in the Northern Canadian Arctic Archipelago from RADARSAT
Vishnu Nandan, Doctoral Student (University of Calgary)

Multi-Frequency Polarimetric Microwave Investigations of Snow Cover on First-Year Arctic Sea Ice
David Babb, Masters Student (University of Manitoba)
Sea ice dynamics
Matthew Gale, Masters Student (University of Manitoba)
Under Ice Primary Production and its Fate in a Coastal Arctic Bay near Resolute Bay, Nunavut
Geoff Gunn, Masters Student (University of Manitoba)
Spatial patterns of phytoplankton response to seasonal ice coverage in Hudson Bay, Canada
Claire Hornby, Masters Student (University of Manitoba)
Oksana Schimnowski, Masters Student (University of Manitoba)
Megan Shields, Masters Student (University of Manitoba)
Rough Sea Ice Surface Deformation and Detection using RADARSAT-2 during the Arctic Melt Season and Its Significance for Polar Bear Habitat
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
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Matt Asplin, Post-Doctoral Fellow (University of Manitoba)
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ABSTRACT

The observed decline in the summer sea ice, in terms of both magnitude and trend, is alarming. We are changing the arctic from one that has been dominated by multiyear sea ice to one that will now be dominated by first-year sea-ice related processes. We can expect a seasonally ice free arctic early in this century. It is important to note that our planet has not had a seasonally ice-free Arctic for at least the past 1.1 million years. This reduction in sea ice is of critical importance to all peoples of the world because of the role that the Arctic plays in the ventilation of the Atlantic and Pacific (Carmack et al. 2006) and because of the large effect that the sea ice albedofeedback mechanism has on acceleration of warming and increased fluxes of green house gases to the atmosphere (due to permafrost melt). Both flora and fauna have evolved over millions of years to take advantage of the presence and timing of the seasonal sea ice life cycle. Now, northern peoples increasingly are finding their traditional way of life under pressure from these changes as they struggle to adapt. Global warming changes both dynamic and thermodynamic processes of snow covered sea ice and these changes have an impact throughout both the physical and biogeochemical cycling in the Arctic marine system. The next few decades will proceed with significant challenges for the Arctic. Marine ecosystems will come under increasing pressure; industrial activity will increase as more exploration and development occurs; and the Inuit people will increasingly find it a challenge to use sea ice for cultural and subsistence purposes. This project will provide sea ice expertise to the coordinated ArcticNet IRISs of the coastal Canadian Arctic, supplying the required information for sound management of these challenges.

KEY MESSAGES

- During the record sea ice minimum of September 2012 the Beaufort Sea became ice free for the first time during the 34 year satellite record. An ice free Beaufort Sea during summer has implications for the natural processes of the Beaufort environment, the potential development of economic activity in the Beaufort Sea, and most importantly for the people that live around and rely on the Beaufort Sea for subsistence.
- Results show that the North Water Polynya ice arch did not form in the years 1993, 1995, 2007 and 2010. For the years 1983, 1990 and 2009 the ice arch did not consolidate at Smith Sound, but rather further north in Nares Strait.
- Initial results from the 2014 CCGS *Amundsen* Cruise showed that on September 1st 2014 a strong wind event occurred resulting in the loss of one of our on ice meteorological towers. During the event, winds were measured at up to 50 km/hr. The wind event was strong enough to break up ice that was 3.6 meters thick.
- We determined key mechanisms for controlling melt pond coverage on un-deformed first-year sea ice: (1) the pre-melt surface topography; (2) the number-density of drainage features that open up through the ice cover; (3) the evolution of ice temperature; and (4) the surface energy balance.
- Key results from our frost flower study showed that salinity and $\delta^{18}O$ values indicated that frost flowers primarily originated from the surface brine skim. Ikaite crystals were observed to form within an hour in both frost flowers and the thin pond ice. Average ikaite concentrations were 1013 $\mu mol\,kg^{-1}$ in frost flowers and 1061 $\mu mol\,kg^{-1}$ in the surface slush layer. Bacteria concentrations generally increased with salinity in frost flowers and the surface slush layer.
- Our pan-arctic marginal ice zone study showed that changes in the physical factors varied amongst regions, and direct effects on organisms were linked to sea ice. Zooplankton species appear to be more flexible and likely able to adapt to variability in the onset of primary production. The major changes identified for the ice-associated ecosystem are with regard to production timing and abundance or biomass of ice flora and fauna, which are related to regional changes in sea-ice conditions.
- Research initiatives from 2014/2015 resulted in 25 publications and a significant amount of data collected on Arctic oceanography, cryosphere physics, sea ice biogeochemistry, and atmospheric science.

OBJECTIVES

1. Continue to collect a spatially and temporally diverse dataset of sea ice characteristics.
2. Continue to develop and improve satellite-based remote sensing of sea ice using an EM sampling program, and physical sampling of sea ice geophysical and electrical properties.
3. Continue to improve our understanding of atmospheric coupling of sea ice dynamics and thermodynamics.
4. Improve our understanding of the consequences from the changes in sea ice on the biological and biogeochemical processes operating across the ocean-sea ice-atmosphere (OSA) interface.

INTRODUCTION

It is now generally accepted that, due to climate change, sea ice is melting with the summer Arctic sea-ice extent decreasing (Serreze et al., 2007; Lindsay et al., 2009) and the remaining summer sea ice thinning (Lindsay and Zhang, 2005 and Kwok and Rothrock, 2009). The September sea ice extent in the Arctic has declined at a rate of 14% per decade with the eight lowest summer sea ice extents since 1979 occurring between 2007 and 2014 (Stroeve et al., 2014; NSIDC 2014). Significant changes have recently been observed in the Arctic sea-ice drift pattern (Kwok et al., 2013) and in sea ice export with changes through Nares Strait (Kwok et al., 2010) and through the Bering Strait (Babb et al., 2013).

The thinning and reduction of the sea ice in the Arctic has resulted in many instances where the ice pack was mischaracterized by satellite data: areas initially interpreted as thick, strong multiyear ice were actually rotting sea ice (where the ice is weak and permeable) (Barber et al., 2009). In 2009 the ice pack was relatively weak and thin, in a single event a strong cyclone created long-period waves that propagated deep into the pack ice, thereby causing swells and the rapid breakup of the sea ice pack (Asplin et al. 2012). This process reduced the floe size into smaller more mobile pieces and increased floe surface area, affecting sea ice dynamic and thermodynamic processes (Asplin et al. 2014). Smaller more mobile ice floes can result in ice motion that has more inertial oscillations, which are harder to forecast or model over short time periods (Barber et al. 2014). Another factor of declining sea ice volume and increasing surface air temperatures in the Arctic is the increase in ice hazards. A recent study documented ice hazards from glacial or thick MYI having keels of more than 30 meters thick and moving faster and in opposing directions to that of the ice pack (Barber et al. 2014). These changes in the sea ice have not only been observed and documented by scientists (Barber et al. 2010, Barber et al. 2012) but have been observed by northern communities and passed down through traditional knowledge (Barber and Barber 2009).

Our group has done a significant amount of research into the interactions between winds, storms and sea ice (e.g. Lukovich et al. 2014, 2011, Asplin et al. 2015, 2014, 2012, Candlish et al. 2014). 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. Another case study documented in 2009, by Asplin et al. (2012), observed long waves from a strong cyclone that propagated deep into the pack ice, thereby causing swells in the ice and the eventual breakup of the sea ice pack. This process reduced the floe size into smaller more mobile pieces and increased floe surface area, and thereby affecting sea ice dynamic and thermodynamic processes (Asplin et al. 2014). With the increase in storm strengths, and the shifting of wind directions during the summer months, modeling of sea ice motion will prove to be more difficult.

Our group studies sea ice and associated Arctic geophysical features from a systems perspective. We look at scales from ice microstructure to hemispheric climatology. Our research is driven by many interlinked objectives, which ultimately will improve our 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.

ACTIVITIES

Amundsen 2014 Field Program

During the summer of 2014 the CCGS *Amundsen* conducted research in the North Water Polyna, Baffin Bay, Beaufort Sea and Chukchi Sea under the ArcticNet initiative. The *Amundsen* expedition was three legs totalling 14 weeks departing July 8th and returning October 12th. The ship's time was divided to allow for continued sampling of the water column at specified stations along the Labrador coast, an iceberg study with in situ sampling, mooring recovery, and on-ice deployment of monitoring instruments and sampling of physical properties. For this project the research on board the CCGS *Amundsen* was divided into two studies: the Upper Air Program and the Beaufort Sea Wind and Sea Ice Motion Study. Each study is described below in more detail.

Participants from our group included research associates M. Ogi, L. Candlish, D. Babb, PhD student K. Komatsu and MSc student H. Stark.

1. Upper Air Program

The upper Atmosphere sampling program was similar to 2013; it was designed to monitor the atmospheric variables that can affect the Arctic atmosphere-ocean interactions. The instrumentation used provided high frequency measurements of temperature, humidity, pressure and wind for the surface up to approximately 20 km. The boundary layer is of particular importance and will was monitored using a Microwave Profiling Radiometer (MWRP) at a frequency of approximately 1s. Atmospheric sampling also included the following:

- Twice-daily RS-92 radiosonde releases capturing variables in Table 1 (These radiosondes were launched at 0000 UTC and 1200 UTC).
- Cloud heights and vertical visibilities measured continuously using the Vaisala CT25K laser ceilometer.
- All-sky camera photos recording true-colour images of the sky and cloud cover. The system consists of a Nikon D-90 camera outfitted with fish-eye lenses with a viewing angle of 160 degrees, mounted in a heated weather-proof enclosure. Images were taken once every 10 minutes.
- Manual meteorological observations of sea state, cloud cover, precipitation type and intensity, etc. were taken hourly. This is important support data for the high-frequency sampling by the MWRP, and ceilometer.
- The continued collaborative research initiative between the University of Manitoba and Environment Canada, Meteorological Service of Canada. Our agreement with EC relates to expanding Arctic observations in support of MetAreas operational forecasting for Environment Canada, and in support of U of M's upper air samping. In 2015, twice daily radiosondes were released and when possible, data were sent to Environment Canada for inclusion in Canadian Meteorological Centre forecasts.
- In 2015, the University was able to deploy one POPs buoys for Environment Canada in the Beaufort Sea and one ice tracking polar SVP buoy on multiyear ice.
- Four times daily manual observations (described above) were also uploaded to the AXYS Automated Voluntary Observation Ship (AVOS) system as part of a Memorandum of Understanding with Environment Canada.

2. The Beaufort Sea Wind and Sea Ice Motion Study

The Beaufort Sea Wind and Sea Ice Motion Study arose from the need for in situ measurements of surface winds and sea ice motion in order to validate a sea ice motion-predicting model. ExxonMobil and CEOS came to an agreement that 9 on-ice towers would be procured along with 9 sea-ice motion beacons, to be deployed during the summer 2014 Canadian Coast Guard Ship (CCGS) *Amundsen* cruise. The network of autonomous equipment was to be deployed on multiyear and thick first year sea ice floes in the Beaufort Sea and left to drift with the icepack. The equipment utilized the iridium satellite communications network and transmits in situ data back to the University of Manitoba. The network provided spatially- and temporally coincident observations on ice drift and the atmospheric forcing mechanisms that govern ice drift. Equipment duration was subject to the stability of the ice floe. The objective was to monitor how ice drift and the ice pack responded to external forcing mechanisms. Figure 1 below shows the cruise path for the CCGS *Amundsen* during leg 2 of the 2014 field campaign.

During leg 2 our goal was to deploy 9 on ice towers. Due to time constraints and lack of helicopter access due to inclement weather we were able to deploy only 5 of these towers. The deployment of each tower required finding the correct type of ice. Typically the ice floes in the area were rotting first year ice, making finding a suitable thick piece of ice difficult. The goal was to find a piece of ice that would survive through the melt and into the fall freeze up, and possibly through to the next summer. Deployment from the ship took approximately 2 hours. Due to time constraints no physical sampling was done. Table 1 shows a summary for the deployment of each on ice tower.

Cambridge Bay 2014 – Ice Covered Ecosystems - CAMbridge bay Processes Studies (ICE-CAMPS)

The principal objective of ICE-CAMPS was to investigate physical and biogeochemical processes operating across the ocean-ice-atmosphere interface during the winter-spring-summer transition to improve our understanding of how our warming climate will affect the ice-covered marine ecosystem of the Canadian Arctic.

The project ran from early March to the end of June 2014. The field camp consisted of two base locations one at the sample location indicated on the map (Figure 2) and the second as a laboratory in the town of Cambridge Bay.

This field campaign was a joint effort among several principal investigators from several different Universities. The field campaign was organized into three research groups.

1. Sea Ice Geophysics Group
2. Marine Biochemistry Group
3. Marine Chemistry Group

Some of the goals from Cambridge Bay were:

- To look at microwave properties of sea ice using a C-band scatterometer.
- Investigate the physical processes controlling the melt evolution.
- Investigate the snow covered first-year ice using remote sensing techniques and in situ measurements.
- Study the exchange of salt, heat, and oxygen between sea ice and the underlying seawater using eddy correlation.
- Assess the productivity and environmental factors affecting ice algae.
- Investigate halogen chemistry across the ocean-sea ice–atmosphere interface.

Participants from our group included PhD students J. Landy, A. Komarov, N. Firoozy, MSc. students M. Shields, M. Mahmood, 4th year honors student P. Carew and network investigator Dr. Yackel.

Table 1. A summary of for the deployment of the On Ice Towers.

Number	Date	Tag duration	# of prey samples	Notes
TDR001	08/13/2014	8 hours	6	Increased freshwater input due to several days of consecutive rain may have slowed down the corrosion of the zinc foil.
TDR002	08/20/2014	41 minutes	0	Whale broke tag off presumably by rubbing against a large boulder while traveling close to shore.
TDR003	08/21/2014	14 minutes	0	Zinc foil corroded prematurely likely because of the large hole in the zinc foil and the fully abraded end cap.
TDR004	08/21/2014	1 hour and 26 minutes	4	Tag stayed on longer because only a small hole was added to the zinc foil. Only two euphausiids were found in the zooplankton samples.

le 1. Summary table of all bowhead whales tagged in Kingnait Fiord, NU.

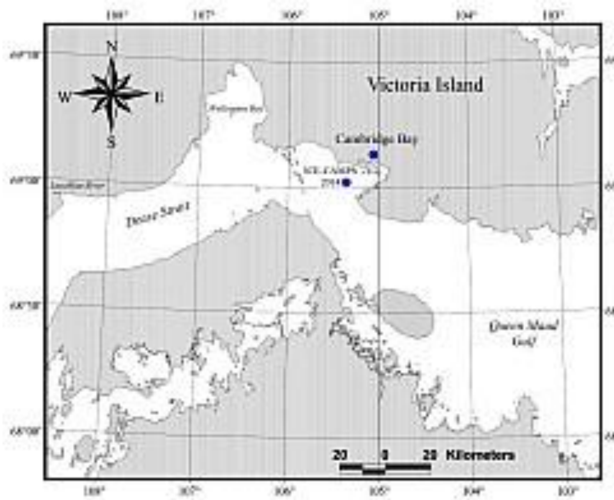

Figure 2. A map of the ICE-CAMPS field location.

Young Sound Campaign 2014

The Daneborg field station is located at 74°18N, 20°13W (Figure 3) and is the outer-fjord research station associated with the larger Zakenberg station, located 25 km further in the fjord. The Daneborg field station is located just next to the Danish Military Station Daneborg, where the Sirius Sledge Patrol is headquartered. The field campaign ran from the end of April 2014 through August.

This field campaign was a joint effort through the international Arctic Science Partnership (http://www.asp-net.org). The sea ice physics group led by Dr. David Barber participated until early July 2014. Participants from our group included PhD student S. Kaur and research associates D. Babb, K. Warner, and G. Gunn.

The Young Sound field campaign mirrored the Cambridge Bay field campaign. Both projects examined at the geophysical properties of snow and sea ice, coincident meteorological and remote sensing data. This will lead to comparisons between the two systems and ultimately leading to increased knowledge of how remote sensing signatures respond to various features in young ice types during the seasonal transition from winter into summer.

Sea-ice Environmental Research Facility (SERF) 2015

On the University of Manitoba campus a salt water pool was constructed to research sea ice growth and the subsequent transport of contaminants. Sea ice is grown and studied under controlled conditions throughout each winter season with 2014/2015 being the fourth winter season of operation. The facility includes an outdoor seawater pool (20 metres long, 10 m wide and 3 m deep). It is equipped with a movable roof to control snow cover and ice growth, and various sensors and instruments to allow real-time monitoring. The SERF facility also includes a trailer laboratory and a storage building.

The 2014/2015 winter campaign ran from December 2014 to February 2015. During this time we investigated the possibility of retrieval of physical properties of bare sea ice from in situ microwave remote sensing measurements.

Time series C-band (5.5 GHz) fully-polarimetric scatterometer data from sea ice during the initial ice formation was collected. The inverse scattering model, as described in the results section (led by PhD student Nariman Firoozy) will be applied to the collected data to reconstruct changes of brine volume content in sea ice. The obtained results will be verified against in situ data.

A flush-mounted antenna was placed on the sea ice surface to measure the complex reflection coefficient in the frequency range between 3 and 6 GHz at different stages of sea ice growth and decay. An algorithm for retrieving physical properties of sea ice from the antenna measurements will be developed.

Figure 3. A map of the field location for Young Sound. Daneborg station (outer fjord) and Zackenberg Station (inner fjord).

RESULTS

A Comparison of Winds over the Beaufort Sea

An example of one of the studies resulting from the 2014 CCGS *Amundsen* field campaign is the comparison of in situ surface winds and re-analysis data sets (led by Lauren Candlish). Near surface winds in the Arctic are used to predict sea ice motion and to study ocean–sea ice–atmosphere processes and large scale circulation patterns. In order to study these processes data sets from ECMWF and NCEP/NCAR are widely used. This study compared the NCEP/NCAR re-analysis data sets with near surface on-ice towers deployed during 2014. Re-analysis data sets use all available data to interpolate wind fields over the high Arctic. Unfortunately the lack of in situ wind data over sea ice means re-analysis data sets have generally stronger winds speeds and large biases akin to those in coastal stations.

On September 1, 2014 a strong wind event occurred resulting in the loss of one of the OITs. During the event winds were measured 50 km/hr. The wind event was strong enough to break up ice that was 3.6 meters thick. Figure 4 shows the winds as measured by the on ice towers for three days leading up to a strong wind event that destroyed one of the on ice towers and the day after the event occurred. The figure 4 also shows the NCEP re-analysis pressure and winds for the region. The NCEP re-analysis data was downloaded from http://www.esrl.noaa.gov. The NCEP u and v component winds and pressure are near surface on the sigma level 0.995. The first tower was deployed on August 27 and the second deployed on August 29 2014. The second tower was deployed on a large piece of ice further from the ice edge and on the far east of the pack. Winds increased on September 1 resulting in the break up of the ice pan where ice station 3 was deployed. On September 2 only two of the towers were operating. The wind event broke up the ice and resulted in the loss of the tower and the position-only ice beacon.

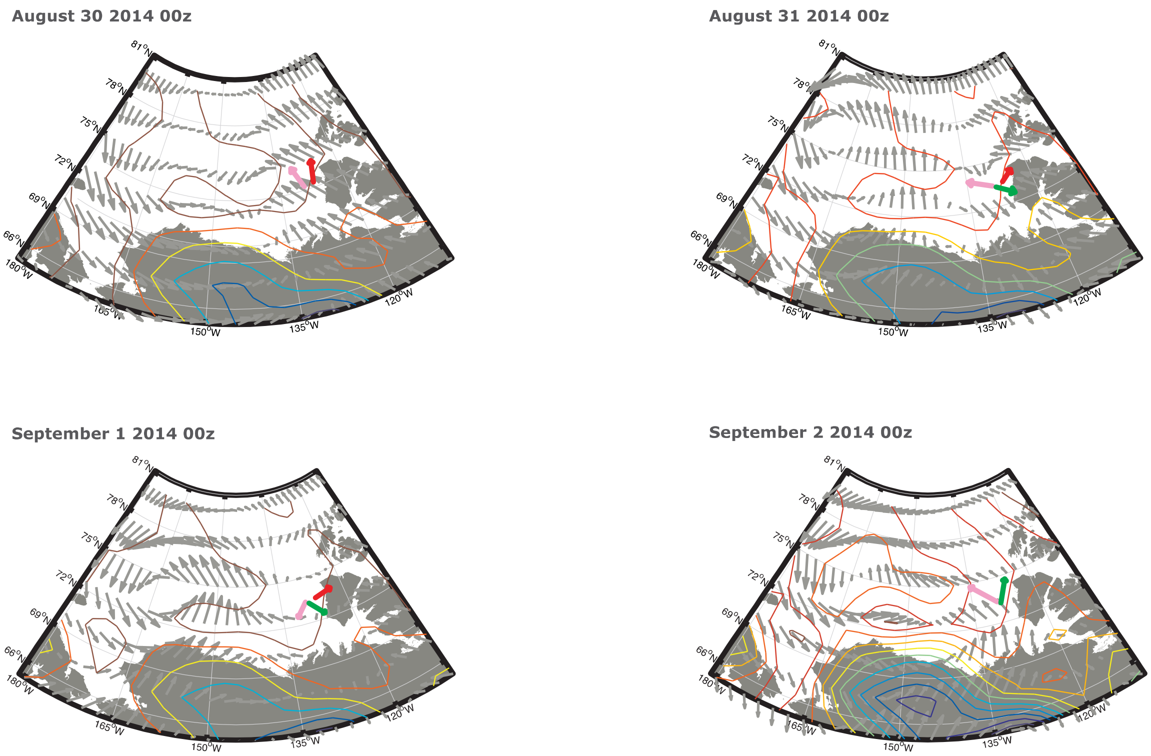

Figure 4. The wind fields and pressure fields from four days leading up to a strong wind event that destroyed one of the on ice towers. In situ wind vectors measured by the on ice towers are shown in pink, red and green, off the coast of Banks Island.

As of Dec 5, 2014 only NCEP re-analysis data is currently available for the time frame. Future work will involve a comparison of data from the ECMWF re-analysis and the NARR re-analysis with the in-situ data. As winds can vary tremendously over a short region it is intrinsically difficult to compare two different measurements unless they are in the same location. Further comparisons over longer time periods are required before any conclusions can be drawn.

Pack Ice thickness measurements in Nares Strait

Ice property data for the pack ice in northern Nares Strait (Kennedy Channel) was collected by Dr. Simon Prinsenberg during late August 2013 with helicopter-borne Electromagnetic-Laser sensor using the helicopter stationed on the CCGS *Amundsen*. The data collection was discussed in the 2013 annual report; only the analysis and results are discussed here.

The pack ice in Kennedy Channel consisted of old First-Year Ice (FYI) and thick Multi-Year Ice (MYI) floes which were either floating freely or embedded in large composite FY-MY ice floes. Ice floes greater than 100m in width had a weighted mean ice thickness by floe width of 2.95 m. When brash ice (<2 m across) was included in the mean thickness calculations, the thickness of the pack ice reduced to 1.94 m (modal 1.78 m), ranging among five transects across Kennedy Channel from 1.75 m to 2.2 m (modal 1.75 m and 1.99 m respectively) (Figure 5). The ice concentrations along the five transects ranged from 51.8% to 81.0%, with a mean of 66.8% and covered up to 23.6 km or 71.5% of the mean width of the Channel. Eliminating the open water within the pack ice, the ice covered only 53% of the mean width of the five transects.

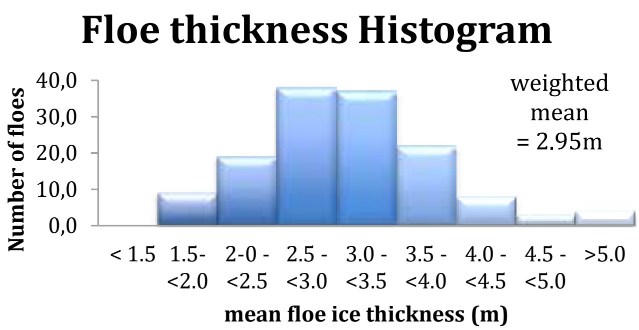

Figure 5. Histogram of the mean floe ice thicknesses of the 140 floes identified in the data set to be wider than 100 m. The weighted mean thickness by floe width is 2.95 m.

A Simple Scheme for Estimating Turbulent Heat Flux over Landfast Arctic Sea Ice from Dry Snow to Advanced Melt

Raddatz et al. (2015) described a dynamic parameter aggregation scheme to estimate hourly turbulent heat fluxes over landfast sea ice during the transition from winter to spring. Hourly albedo measurements were used to track the morphology of the surface as it evolved from a fairly smooth homogeneous dry snow surface to a rougher heterogeneous surface with spatially differential melting and melt ponds. The estimates of turbulent heat fluxes for 928 hours were compared with eddy-covariance measurements. The model performance metrics (W m^{-2}) for sensible heat flux were found to be: mean bias = -3, root-mean-square error = 6 and absolute accuracy = 4; for latent heat flux they were: near zero, 3 and 2, respectively. The correlation coefficient between modelled and measured sensible heat fluxes was 0.82, and for latent heat fluxes, it was 0.88 (Figure 6). The turbulent heat fluxes were estimated more accurately without than with adjustments for atmospheric stability based on the bulk Richardson number. Overall, and across all metrics for both sensible and latent heat fluxes, the dynamic parameter aggregation scheme outperformed the static Community Ice (C-ICE) scheme, part of the Community Climate System model, applied to the same winter-to-spring transition period.

Ice Free Beaufort Sea During September 2012

Babb et al. (2015) examined the physical processes that contributed to an ice-free Beaufort Sea during September 2012. The data was collected as part of the 2012 season of the BREA field campaign. This campaign was described in the 2012 and 2013 annual report; only the analysis and results are discussed here.

During the record sea ice minimum of September 2012 the Beaufort Sea became ice free for the first time during the 34 year satellite record. Using a combination of in situ and remotely-sensed observations we monitored the thermodynamic evolution of a 5 m thick multiyear ice floe during spring and early summer in the Beaufort Sea. We note an extraordinarily large amount of bottom melt, which we ascribe to an accelerated ice-albedo feedback loop that was fostered by a 111% anomaly in the cumulative solar heat input through areas of open water in the Beaufort Sea. The positive anomaly in solar heat input began during May, when sea ice concentrations declined earlier than they had historically, and increased during June and July when reduced sea ice concentration around the solar maximum enhanced solar heat input. Premature breakup of the Beaufort ice pack and negative anomalies in sea ice concentration are ascribed to preconditioning towards younger and thinner ice types. As a result of preconditioning and reduced ice coverage the cumulative solar heat input through areas of open water in the Beaufort Sea increased significantly at a rate of 12.9 MJ m^{-2} $year^{-1}$ between 1979 and 2012, which is sufficient heat to drive an additional 4.3 cm $year^{-1}$ of bottom melt. Overall the Beaufort icepack has become more susceptible to melt and may become seasonally ice free more frequently in coming years. An ice-free Beaufort Sea during summer has implications for the natural processes of the Beaufort environment, the potential development of economic activity in the Beaufort Sea, and most importantly for the people that live around and rely on the Beaufort Sea for subsistence.

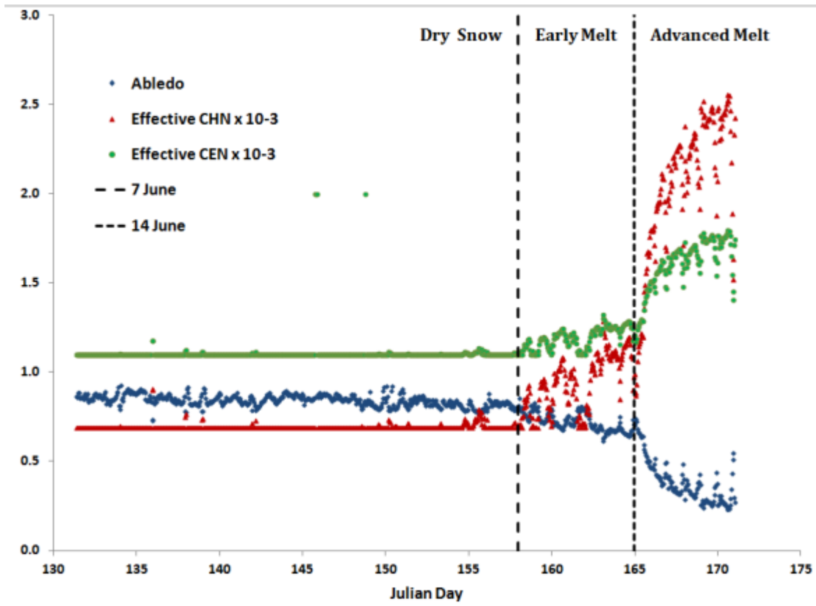

Figure 6. The albedo, effective CHNx103 and the effective CENx103 as the season progressed from winter to spring. Where CHN and CEN are, respectively, the neutral transfer coefficients for sensible and latent heat fluxes.

Microwave Scattering of Sea Ice

Data for this project was acquired as part of the Cambridge Bay 2014 field campaign in Dease Strait. The initial project, led by Megan Shields, was to study the microwave scattering from sea ice pressure ridges, however the project needed to be changed due to the area having only flat ice. The roughest ice found in the project area was only slightly deformed sea. Based on the field conditions the project is now to examine small-scale surface topography changes over a three-week period in May. A Leica ScanStation C10 discrete-pulse terrestrial laser scanner was used with High Definition Surveying (HDS) targets to scan a non-invasive sampling site from three locations in order to create a three-dimensional digital point cloud model. The time of flight for each laser pulse emitted by the scanner are recorded once reflected and returned to the scanner from the surfaces of surrounding objects creating a three-dimensional point cloud. The scanner emits pulses at frequencies up to 50 kHz and at a wavelength of 532 nm. Figure 7 is a screenshot of a point cloud model of the non-invasive sampling site in Dease Strait. Scanning platform locations are shown as blue rectangles and HDS target locations are shown as red tripods (yellow numbers point to the location). Measurement values around the sampling site are displayed in metres. Figure 8 shows point cloud models from Dease Strait mapped by elevation. Red represents areas of highest elevation and blue represents areas of lowest elevation. This figure shows how the surface topography changed over the sampling dates due to weather (i.e. wind and precipitation).

The North Water Polynya Ice Arch: Changes in the Formation and Dissolution from 1979 – 2012

The North Water Polynya (NOW) is one of the most biologically productive marine areas in the Arctic. The polynya typically forms in early spring and is heavily dependent on the consolidation of ice in Nares Strait during the winter months. Ice advecting from the Arctic Ocean in winter will become lodged in Nares Strait, consolidates, and eventually forms an arch spanning the strait from Ellesmere Island to Greenland. With the changing icescape in the Arctic, the long-

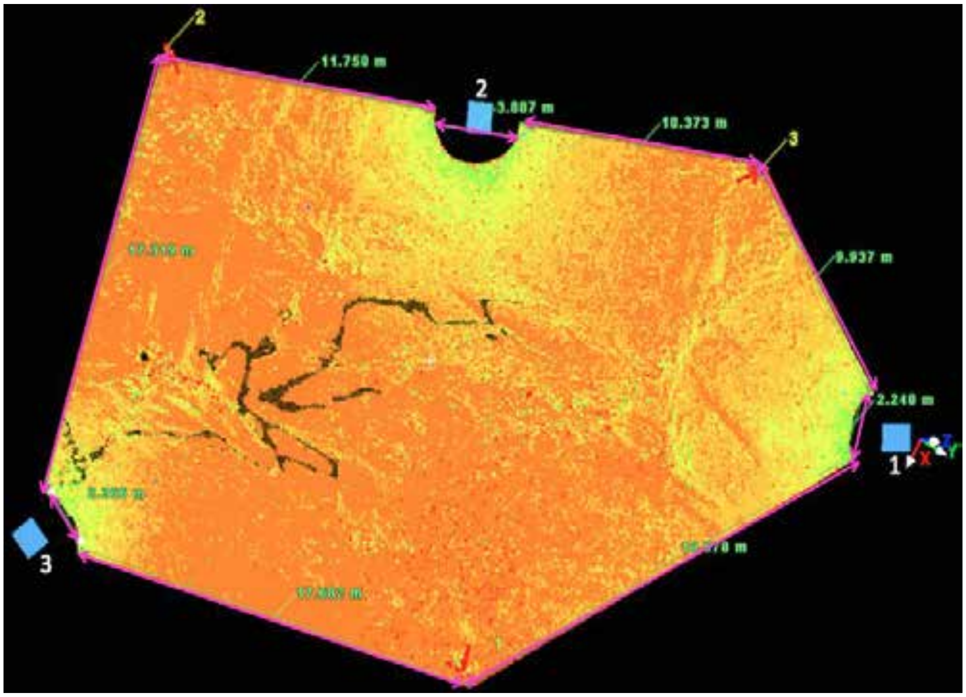

Figure 7. Point cloud model of the non-invasive sampling site in Dease Strait. Scanning platform locations are shown as blue rectangles and HDS target locations are shown as red tripods (yellow numbers point to the location). Measurement values around the sampling site are displayed in metres.

term impacts and variability of the arch formation are unknown. This study (led by Heather Stark) examined the variability of the NOW formation and dissolution using SSM/I sea ice concentration dataset from 1979 – 2012. AMSR-E imagery was used to validate the trends extracted from the SSM/I dataset.

Results from this study show that the ice arch did not form in the years 1993, 1995, 2007 and 2010. Interestingly, for the years 1983, 1990 and 2009 the ice arch did not consolidate at Smith Sound, but rather further north in Nares Strait. Figure 9 shows for years from when the ice bridge consolidated as a typical year, in a more northern location, when there was no ice arch and when there was an early formation.

Further analysis was done to look at trends in the formation and dissolution of the ice arch. The average number of days the polynya remained open was 82, with the minimum being 48 occurring in 1987 and the maximum was 144 days occurring in 2006. The formation and dissolution of the ice arch is occurring earlier each year. The earlier formation is possibly caused by thinner sea ice, which would be more easily advected out of the region by the ocean currents and winds. An earlier dissolution may be caused by thinner sea ice melting faster and a longer melt season.

The Delivery of Organic Contaminants to the Arctic Food Web: Why Sea Ice matters

For decades sea ice has been perceived as a physical barrier for the loading of contaminants to the Arctic Ocean. Pucko et al. (2015) show that sea ice, in fact, facilitates the delivery of organic contaminants through processes that are independent of contaminant physical-chemical properties and therefore, differentiate between contaminants (e.g. atmospheric loading of contaminants to melt ponds over the summer and their subsequent leakage to the ocean).

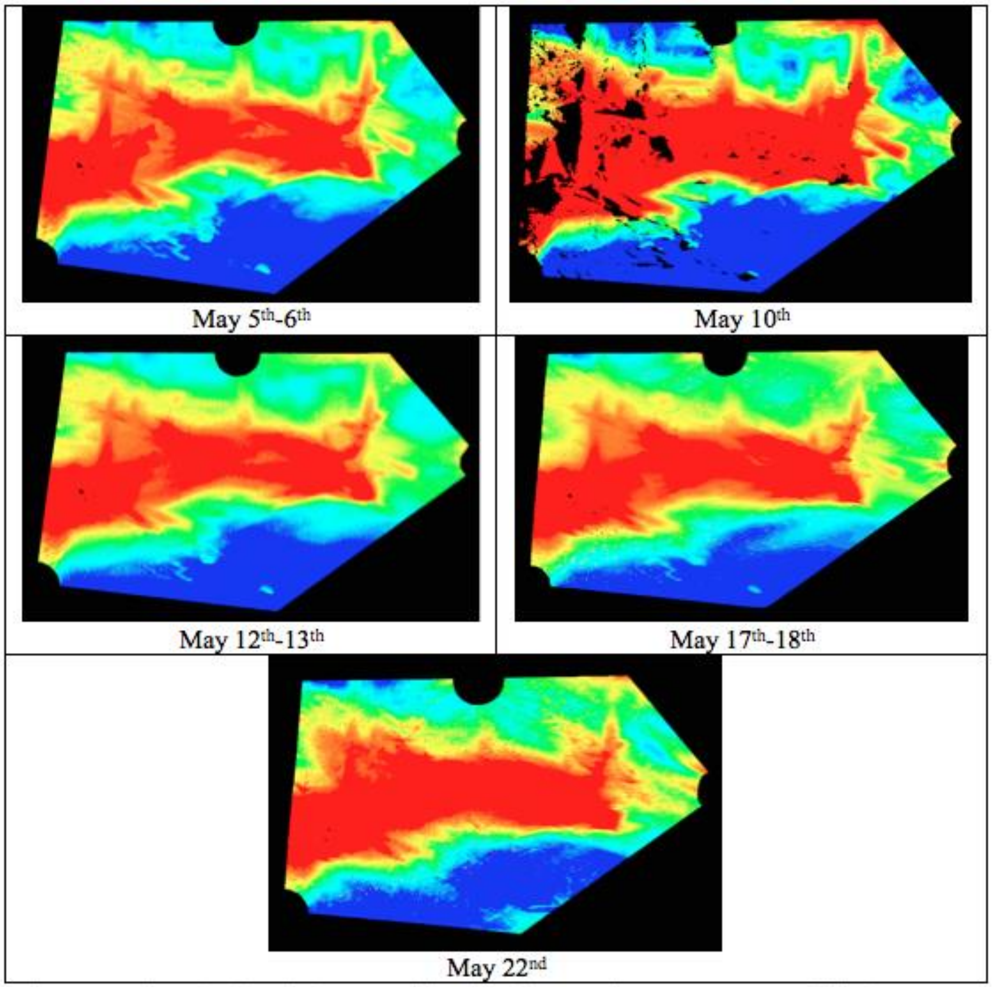

Figure 8. Point cloud models from Dease Strait mapped by elevation. Red represents areas of highest elevation and blue represents areas of lowest elevation.

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

Reconstruction of Snow-Covered Sea Ice Dielectric Profiles through Normalized Radar Cross Section Data Inversion

Through the work done at SERF and in Cambridge Bay, this study (led by Nariman Firoozy) looked at the electromagnetic parameters of snow-covered sea ice profiles from normalized radar cross section (NRCS) data. To achieve this, a global optimization inversion algorithm in conjunction with a forward solver model was developed. NRCS measurements were carried out to evaluate the algorithm by using scatterometer data collected during the SERF campaign in 2014 and the Cambridge Bay Campaign 2014. Scattermometer data is extremely fine resolution and uses various bands, any look angle, and a small scale making it ideal to for model validation.

Figure 10 describes the problem statement and how the forward and inverse models were developed. While figure 11 shows the forward solver and the inverse solver models.

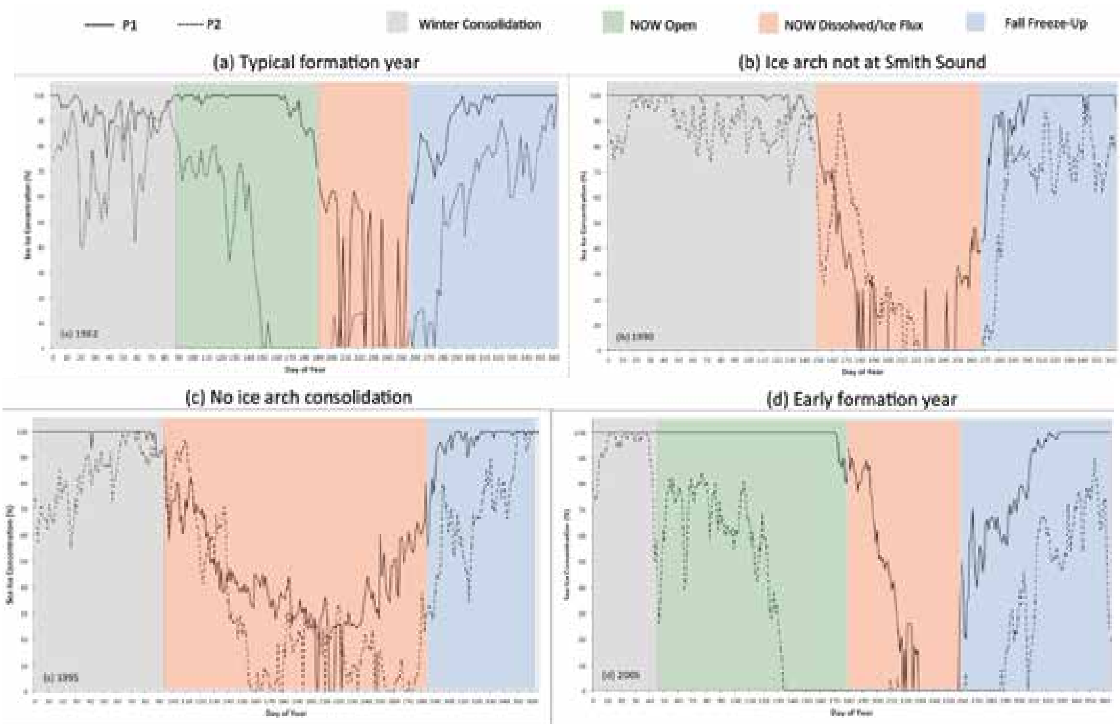

Figure 9. Comparisons of typical and atypical polynya formation years.

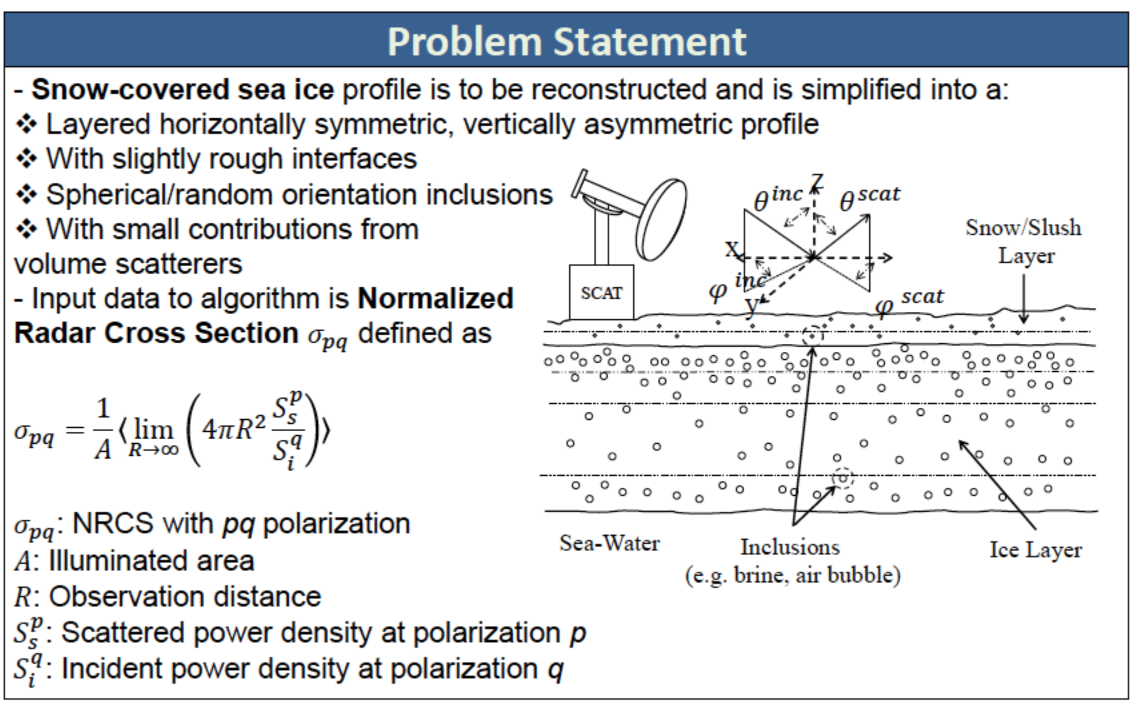

Figure 10. The simplified profile from which the forward and inverse model was developed.

❑ ***Forward Solver:***

- **Boundary Perturbation Theory (BPT)** as a forward solver model, calculates the polarimetric NRCS of the simplified media

$$\sigma_{pq} = \pi k_0^2 \sum_{n=0}^{N-1} \left|\alpha_{pq}^{m,m+1}\left(k_\perp^{scat}, k_\perp^{inc}\right)\right|^2 W_n\left(k_\perp^{scat} - k_\perp^{inc}\right) + \pi k_0^2 \sum_{i \neq j} Re\{\alpha_{pq}^{i,i+1}\left(\alpha_{pq}^{j,j+1}\right)^*\} W_{i,j}\left(k_\perp^{scat} - k_\perp^{inc}\right)$$

$k_\perp$: Perpendicular projection of wave propagation vector on surface

α: Complex recursive reflection-based coefficients

- Spatial power density *W* is measured to follow an exponential distribution:

$$W_{Exponential} = \frac{(hl)^2}{2\pi} \frac{1}{\left(1 + |k_\perp^{scat} - k_\perp^{inc}|^2 l^2\right)^{3/2}}$$

❑ ***Inverse Solver:***

- **Differential Evolution (DE)** algorithm, based on evolution minimizes a misfit functional as an indicator of discrepancy between true and retrieved profile

$$F(\chi(r)) = \sum_{i=1}^{nf} \left(f_i^2 \sum_{\zeta=1}^{nf} f_\zeta^{-2}\right)^{-1} \sum_{n=1}^{nRx} \sum_{m=1}^{nTx} \sum_{p=H,V} \sum_{q=H,V} \frac{\sigma_{HH}^{meas}(\Psi_{inc}^m, \Psi_{scat}^n, f_i)}{\sigma_{pq}^{meas}(\Psi_{inc}^m, \Psi_{scat}^n, f_i)} \times \left|\sigma_{pq}^{meas}(\Psi_{inc}^m, \Psi_{scat}^n, f_i) - \sigma_{pq}^{sim}(\chi(r), \Psi_{inc}^m, \Psi_{scat}^n, f_i)\right|$$

Ψ_{inc}^m: *m*th incident look angle

Ψ_{scat}^n: *n*th scattered look angle

f_i: *i*th sample frequency

s: BPT simulated NRCS

σ^{meas}: Either measured or synthetically produced NRCS

- To tackle the ill-posedness of the problem, a projection-based regularization scheme is utilized.

Figure 11. The forward and inverse solver models.

The inversion algorithm was applied to the NRCS measurements carried out in February 2014 at the SERF pool. From various inversion results, we can conclude that the inversion above had 50 input data points. Inclusion of more measurement angles and frequencies will increase the retrieval accuracy. Lower frequencies will result in better reconstruction for deeper ice layers due to penetration depth. The top layer is slushy rather than dry snow and hence shows a very high permittivity. Age of ice, the high permittivity of layers and low cross polarization values makes the application of a surface scattering model justifiable. The necessity of incorporating a priori information may be minimized by including more input NRCS data points and the use of a bistatic configuration.

Surface and melt pond evolution and sea ice surface roughness

Landy et al. (2014) and (2015) used LIDAR measurements taken during the 2011 and 2012 Resolute Bay field campaigns to study the surface and melt pond evolution and the sea ice surface roughness. The Resolute Bay 2011 and 2012 field campaigns were described in previous ArcticNet reports, thus only the results are discussed here.

A terrestrial LiDAR instrument was used to collect three-dimensional measurements of the surface topography and mass balance of first-year sea ice near Resolute, NU, from two consecutive years. These measurements were used to examine the factors affecting spatial and temporal variations in melt pond coverage. Results showed that the key mechanisms controlling melt pond coverage on un-deformed first-year sea ice were: (1) the pre-melt surface topography; (2) the number-density of drainage features that open up through the ice cover; (3) the evolution of ice temperature; and (4) the surface energy balance. A particularly interesting discovery was that the roughness of the pre-melt topography controlled the rate of melt pond spread or recession as a function of the net meltwater balance (production minus drainage) at the ice surface (Figure 12). For instance, an equivalent change in the meltwater balance caused ponds to spread or recede over an area that was almost 90% larger in 2012 (smoother surface) than in 2011 (rougher surface).

Landy et al. (2015) developed a technique for calculating 2-D centimetre-scale sea ice surface roughness parameters from 3-D terrestrial LiDAR data (Figure 13). The technique involves: data pre-processing, sophisticated Fourier-based detrending and 2-D autocorrelation. Roughness parameters calculated over a variety of sea ice surfaces, including: congelation ice, snow, frost flowers and pancake ice, were compared to parameters calculated using conventional 1-D profiling techniques, and were found to be considerably more precise. The 2-D technique can characterize roughness as a stationary single-scale process, which the 1-D technique typically cannot. Sea ice surfaces were found to have strongly anisotropic correlation functions, and our results also show there was no fundamental relationship between the RMS height and correlation length parameters for sea ice, contrary to popular belief.

Polynya impacts on water properties in a Northeast Greenland Fjord

Results from the 2014 Young Sound field campaign are described by Dmintrenko et al. (2015). Between October 2013 and May 2014, four landfast ice-tethered moorings were deployed from the stationary landfast ice in Young Sound. A storm event during late December 2013 with down-fjord winds of up to 25 m/s forced the collapse of the landfast ice over the Young Sound (YS) fjord outlet in northeast Greenland. This storm created a coastal polynya that was further maintained by several consecutive wind events until early March 2014.

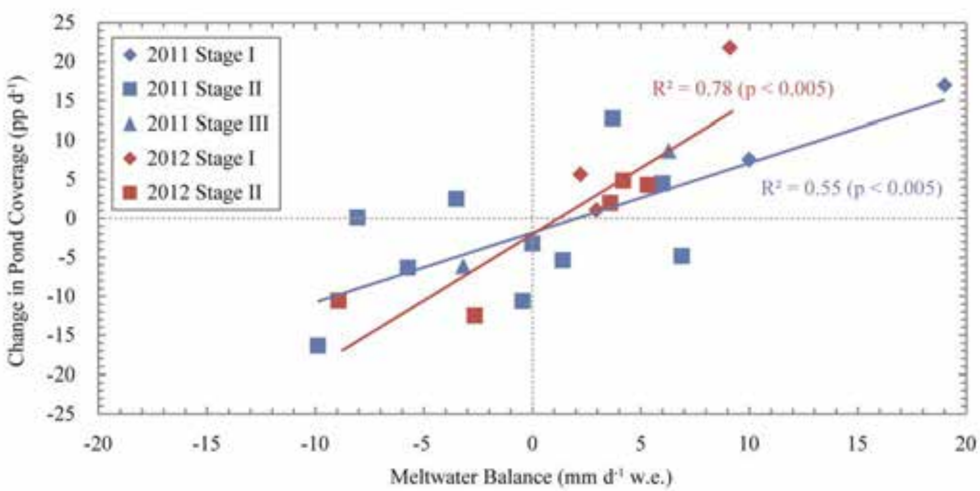

Figure 12. Change in melt pond coverage (in percentage point per day) associated with a change in meltwater balance (in mm per day) on melt-pond covered landfast first-year sea ice.

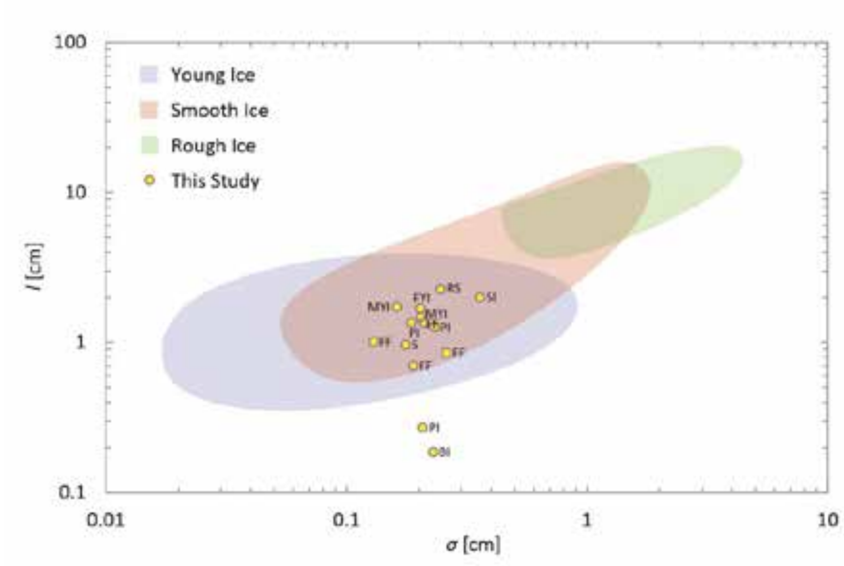

Figure 13. Comparison between the centimetre-scale RMS height and correlation length of fourteen sea ice surfaces. Literature values, grouped as young ice (obtained in the laboratory or field), smooth ice (FYI or MYI, obtained in the field only), and rough ice (FYI or MYI, obtained in the field only), are presented as shaded zones in the background.

During winter 2013–14 the gravity current of dense and brine-enriched polynya-modified water enhanced the inflow of water between 40 and 140 m to the interior of the fjord with a corresponding outflow in the surface layer (~0–40 m). Mean velocities within the surface layer were 2–4 cm/s while velocities within the lower layer were 1–2 cm/s. This is evident from both (i) ADCP velocity observations at three landfast ice-tethered oceanographic moorings and (ii) lagging observed in the time series of salinity and temperature at two outer-fjord moorings separated by 5.14 km. The CTD data taken in May 2014 show that the intermediate layer in the outer and mid-fjord were filled with cool, saline and oxygen enriched polynya water. Our bulk estimates show that the circulation cell over the fjord-side of the entrance sill was not closed and inflow of polynya-modified coastal water to YS over the sill was required to explain the fall-to-winter salinity increase in YS. The data show the role of a coastal polynya in ventilating the fjords interior down to ~140 m while not deep enough to replace the bottom water (Figure 14).

Frost flowers on young Arctic sea ice: The climatic, chemical, and microbial significance of an emerging ice type

Barber et al. (2014) used data from the Young Sound campaign in 2012 to look at the growth of frost flowers on young sea ice and validate a model of frost flower growth and ablation. This was done by cutting a pond in first year sea ice at the mouth of Young Sound in north-east Greenland. As soon as new ice started to form expanding clusters of frost flowers began to develop. These frost flowers were 5°C colder than the brine surface, with an approximately linear temperature gradient from their base to their upper tips. Results from this study were:

- Salinity and $\delta^{18}O$ values indicated that frost flowers primarily originated from the surface brine skim.
- Ikaite crystals were observed to form within an hour in both frost flowers and the thin pond ice.

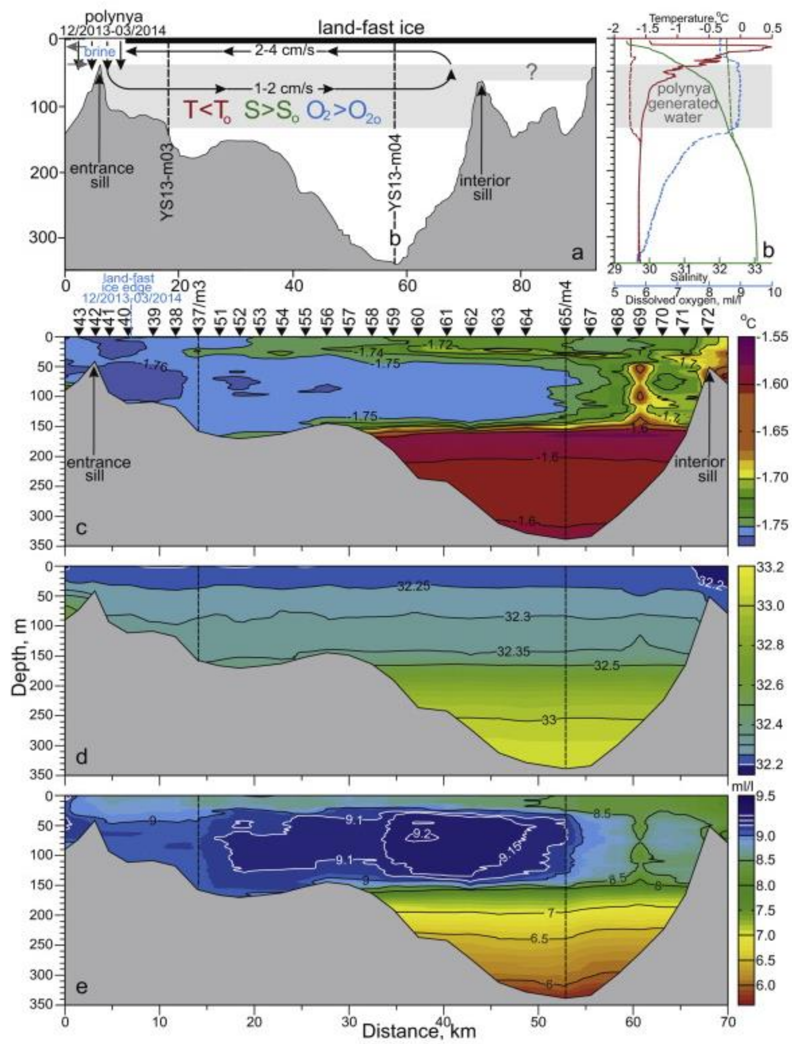

Figure 14. (a) Schematic depiction of polynya impact on the YS circulation. (b)Vertical distribution of temperature (red, °C), salinity (green) and DO (blue, ml/L) in 10/26/2013 (solid lines, temperature and salinity only) and 5/5/2014 (dashed lines) at mooring YS13-m04. (c–d) The along-fjord transect of (c)temperature (°C), (d) salinity and (e) DO (ml/L) taken in 5/10-12/2014 shows the polynya generated cool, saline and oxygen enriched water in ~40–140 m. (c) Black triangles on the top identify positions of CTD stations. (c–e) Black and blue dashed lines show locations of the landfast ice-tethered moorings YS13-m03/m04 and landfast ice edge for 12/2013-03/2014, respectively.

- Average ikaite concentrations were 1013 µmol kg^{-1} in frost flowers and 1061 µmol kg^{-1} in the surface slush layer.
- Bacteria concentrations generally increased with salinity in frost flowers and the surface slush layer.
- Bacterial densities and taxa indicated that a selective process occurred at the ice surface and confirmed the general pattern of primary oceanic origin versus negligible atmospheric deposition.

This study was a collaborative effort with Drs. T. Papakyriakou and S. Rysgaard and their respective ArcticNet projects.

Selected physical, biological and biogeochemical implications of a rapidly changing Arctic Marginal Ice Zone

Another study led by Dr. Barber was a review paper on the physical, biological and biogeochemical process in the marginal ice zone (MIZ). This manuscript has been accepted to a special volume in the journal Progress in Oceanography. This study was a collaborative effort with Drs. J.E. Tremblay and S. Rysgaard and their respective ArcticNet projects.

This Pan-Arctic review summarized the main changes in the Arctic ocean-sea ice-atmosphere (OSA) interface, with implications for primary- and secondary producers in the ice and the underlying water column. Changes in the Arctic MIZ were interpreted for the period 1979-2010, based on best-fit regressions for each month. Trends of increasingly open water were statistically significant for each month, with quadratic fit for August-November; illustrating particularly strong seasonal feedbacks in sea-ice formation and decay. Geographic interpretations of physical and biological changes were based on comparison of regions with significant changes in sea ice: 1) The Pacific Sector of the Arctic Ocean including the Canada Basin and the Beaufort, Chukchi and East Siberian seas; 2) The Canadian Arctic Archipelago; 3) Baffin Bay and Hudson Bay; and 4) the Barents and Kara seas. Changes in ice conditions in the Barents Sea/Kara Sea region appear to be primarily forced by ocean heat fluxes during winter, whereas changes in the other sectors appear to be more summer-autumn related and primarily atmospherically forced. Effects of seasonal and regional changes in OSA-system with regard to increased open water were summarized for photosynthetically available radiation, nutrient delivery to the euphotic zone, primary production of ice algae and phytoplankton, ice-associated fauna and zooplankton, and gas exchange of CO_2. Changes in the physical factors varied amongst regions, and showed direct effects on organisms linked to sea ice. Zooplankton species appear to be more flexible and likely able to adapt to variability in the onset of primary production. The major changes identified for the ice-associated ecosystem are with regard to production timing and abundance or biomass of ice flora and fauna, which are related to regional changes in sea-ice conditions.

Variability of C-Band Backscatter Signatures of Summer Sea Ice

With increased global interest of marine shipping and industrial development in the Canadian Arctic, it is extremely important for both safe operations and travel to have methods of detection and monitoring ice features that pose possible risks. A study led by Kerri Warner used data from the CCGS *Amundsen* field programs from 2009 to 2013 to characterize the electromagnetic signatures of different ice types including new ice, first year ice, multiyear ice and extreme ice features.

There was a significant amount of variability in the microwave backscattered signatures of sea ice obtained during the warm season. A possible threat for industrial activity or marine shipping can be seen when comparing signatures obtained from newly forming ice against rotten multiyear ice. The newly forming sea ice (approximately 6-10 cm thick) had similar backscattered signatures as rotten multiyear ice (approximately 2 m thick). While there were numerous geophysical and thermodynamic parameters at play, ultimately it was warm temperatures that caused melt water to be present at the surface of both of these distinctly different ice types. The water in liquid phase caused the active microwave to scatter from the surface, not allowing any scattering to occur from within the volume.

DISCUSSION

Amundsen

The Amundsen project was continued in a similar manner to past campaigns with results being analyzed for new projects. This however is the first year when a network of autonomous on ice meteorological towers was deployed. This will be continued in 2015 with an additional 4 towers to be deployed in the Beaufort Sea.

SERF

We continued to develop a deeper understanding of the thermal-dielectric nature of snow covered sea ice using the Sea Ice Environmental Research Facility (SERF) located on the University of Manitoba campus. Results from Nariman Firoozy show that the inverse and forward scattering models are similar to that measured in SERF and in the Cambridge Bay field campaign. The SERF facility will continue to be utilized in future years to further develop and validate the models.

Cambridge Bay

In 2014, the ICE-CAMPS projects investigated physical and biogeochemical processes operating across the ocean-ice-atmosphere interface during the winter-spring-summer transition in Dease Strait.

As part of a community outreach program the ICE-CAMPS field program included an educational event called Arctic Science Day, hosted by ICE-CAMPS participants and ArcticNet's Schools on Board. Arctic Science Day involved 35 students in grades 7 through 12 and four teachers from the Killinik High School in Cambridge Bay who visited our ice camp, resulting in a unique learning opportunity for the students and teachers to interact with scientists and learn about the research being conducted locally. Due to this Arctic Science Day, one student and teacher participated in the 2014 Schools on Board program.

Initial results from Cambridge Bay were given by Megan Shields' study on Microwave Scattering of Sea Ice and by Nariman Firoozy in his validation of the forward and inverse model.

Young Sound

Some of the first analysis to come from the Young Sound 2014 field season included Igor Dmintrenko's manuscript on the Polynya Impacts on Water Properties in a Northeast Greenland Fjord. Previous field seasons from Greenland resulted in Barber et al. (2014) as well as collaborations with Galley et al. (2015) and Sviers et al. (2015).

The next field location in Greenland will be moved further north to Station Nord, which will begin in April 2015 and is organized through the Arctic Science Partnership.

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.

The objectives for this project were explored through the field campaigns and the studies completed this year. Specifically each of our four objectives were addressed:

1. Through the in-situ field programs of Cambridge Bay, Young Sound and the CCGS *Amundsen* we collected sea ice thickness tran-

sects, temperature profiles, salinity profiles, sea ice extent, and other sea ice properties. Meta data was loaded into the Canadian Polar Data Catalogue, and is available upon request.

2. Through the work at SERF, Cambridge Bay and from the analysis of EM data from previous field seasons we continued to develop models and improve our understanding of the electromagnetic signatures of various types of sea ice. Our research has led to the European Space Agency (ESA) using our theories (and observations) to create a new tools for scientists and managers in anticipation of future Copernicus SAR constellation missions and the technology is also being used by oil an gas companies as well as the Canadian Ice Service (CIS) to develop new ice management tools.
3. Through our in situ field programs and our long running atmospheric sampling program on board the CCGS *Amundsen* we have been able to monitor atmospheric conditions and the sea ice motion. We have also been able to collaborate with partners such as Environment Canada and ExxonMobil to improve forecasting in a marine environment and to add in the development of an ice motion model.
4. Through the studies led by Dr. David Barber and our collaborative nature at the Centre for Earth Observation Science we have been able to improve our understanding of the consequences on the biological and the biogeochemical processes operating across the OSA interface.

This project has contributed to the knowledge base with over 25 publications from April 2014 through March 2015. Our research group has participated in four large field programs and two community Arctic Science Days, one in Winnipeg in March 2015 and one in Cambridge Bay during the field campaign during spring 2014.

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FRESHWATER-MARINE COUPLING IN THE HUDSON BAY IRIS

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HQP

Pamela Godin, Doctoral Student (University of Manitoba)
The impacts of permafrost degradation on the carbon budget of Hudson Bay
Mukesh Gupta, Doctoral Student (University of Manitoba)
Role of surface roughness in moderating ocean-sea ice-atmosphere processes within the Marginal Ice Zone
Peter Hülse, Doctoral Student (Memorial University of Newfoundland)
Climatic controlled freshwater discharge patterns in southeastern Hudson Bay and Labrador since the Medieval Warm Period
Vlad Petrusevich, Doctoral Student (Centre for Earth Observation Science (CEOS))
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James Williams, Doctoral Student (McGill University)
Amelie Bouchat, Masters Student (McGill University)
Energy dissipation in viscous-plastic sea ice models
Patricia DeRepentigny, Masters Student (McGill University)
Finding the source regions of sea ice melting in the marginal ice zone: a Lagrangian approach
Annie Eastwood, Masters Student (University of Manitoba)
Melissa Gervais, Masters Student (McGill University)
Geoff Gunn, Masters Student (University of Manitoba)
Spatial patterns of phytoplankton response to seasonal ice coverage in Hudson Bay, Canada
Yukie Hatta, Masters Student (McGill University)
Mechanical properties of sea ice within the Canadian Arctic Archipelago
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ABSTRACT

Climate models predict warming in the Hudson Bay watershed that may alter the amount and timing of runoff and hence, of the load of suspended solids, dissolved organic matter and other major nutrients, and heat delivered to the Bay. In the Churchill and Nelson estuaries, such changes will be superimposed on earlier changes in the hydrological regime; diversion of Churchill River flows into the Nelson River and a shift of a third of total discharge from summer to winter. Our study of transfer pathways through river estuaries into Hudson Bay will improve our understanding of the effects of these changes. The overarching objective of this project is to describe the impact of freshwater quality and quantity on marine processes within Hudson Bay. In particular we are interested in understanding the principal processes which couple the freshwater and marine systems in Hudson Bay and to examine the cumulative impacts of climate change and hydroelectric development on Hudson Bay. Our key industry partner (Manitoba Hydro) will use this information to examine aspects of environmental impacts due to development of dams along the Nelson River, including the planned development of Conawapa Generating Station. More specifically our team will determine the fluxes, pathways and fate of suspended solids and dissolved organic matter transferred through the Churchill and Nelson estuaries during the open water season when mixing in the estuary is determined by wind-driven waves, tides and fluvial and marine currents, and under ice, when mixing is determined by tides and fluvial and marine currents alone. We will also investigate the relative significance of fluvial loading and littoral resuspension to concentrations of suspended solids in the estuaries and Hudson Bay and to study the effect of suspended solids and dissolved organic matter on radiative transfer in the estuary and nearby Hudson Bay. This team will also investigate historical effects of climate on Hudson Bay by interpretation of data stored in bottom sediments within our three supersites - the estuaries of the Nelson and Churchill Rivers, and of the Grande Rivière de la Baleine - and also in sediments deposited at the Bay-wide scale.

KEY MESSAGES

1. Dr. Zou Zou Kuyzk will continue the field programs in Hudson Bay through a new project for the final phase of ArcticNet.
2. We demonstrated the existence of a large coastal polynya in northwestern Hudson Bay. Measuring approximately 600 km long by 60 km wide, this polynya was typically opened and maintained by surface winds for periods of one to five days. Closing mechanisms result from decline in wind maintenance and apparent thermodynamic ice formation. Open water is present on the northwest coast at some size for up to 70% of the winter between ice formation and breakup.
3. The polynya in northwestern Hudson Bay likely affects biota from autotrophs to pinnacle carnivores. The icescape of the region is an important habitat for the western Hudson Bay Polar Bears; a solid barrier to air for overwintering marine mammals; and a growth medium for ice algae and pelagic phytoplankton.
4. The Hudson Bay regional assessment has shown that the Port of Churchill has a shipping season of 14 weeks, from July 15th to October 31st. Between 2009 and 2014, the grain shipping season typically ran from early August to late October and averaged 11.2 weeks in length.
5. We can project with high confidence that the open water season in Hudson Bay will lengthen by a month or more over the next 30 years, but there are remaining uncertainties for an assessment of ice hazards, forecasts, and infrastructure operations in shipping and navigation.

While enhanced variability in summer surface winds due to changes in cyclonic and storm activity will have implications for shipping and navigation in the Hudson Bay region, there is a limited basis to project that the currently observed small trends will change in the future. There is no indication that extreme events have changed, or will change sufficiently to positively or negatively impact transportation operations in Hudson Bay.

OBJECTIVES

During the tenure of this project we addressed a number of interrelated objectives that were designed to gain insights into the processes which control freshwater-marine coupling in Hudson Bay. The following objectives highlight the program:

1. To advance knowledge of spatial and temporal variability in the dynamic and thermodynamic forcing of sea ice by freshwater, both within Hudson Bay, and relative to other regions of the Arctic.
2. To determine sources, fluxes and sinks of suspended sediments, particulate and dissolved organic matter (DOM) over the seasonal cycle in Hudson Bay.
3. To determine how freshwater fluxes affect the marine ecosystem, biogeochemical processes and contaminant transport (through collaboration with other teams in our IRIS).
4. To determine how sea ice affects freshwater-marine coupling and associated marine ecosystem function particularly in terms of the dynamics freshwater plumes under sea ice.
5. To understand the significant role played by the boundary current in the freshwater budget of the system, and its sensitivity to wind-forcing.
6. Through these studies to determine the relative roles of climate change on shipping and transportation in Hudson Bay.

INTRODUCTION

Hudson Bay is central to Canada's history and geography. History records the Bay as a meeting ground for the First Nations and Inuit; a gateway to European exploration following the ill-fated voyage of Henry Hudson; a battleground for fur and imperial influence over the continent; and most-recently a sea route for grain and minerals from the Canadian interior to the global economy. The larger scientific community has largely overlooked Hudson Bay until recent years (Stewart and Barber 2010); this project has helped to rectify this oversight.

Arctic sea ice is one of several components of the freshwater Arctic Ocean budget, studied in the 1960s by Timofeev (1960) and Mosby (1962) and continues to be addressed (Aagaard and Carmack, 1989, Serreze et al., 2006 and White et al., 2007). Due to variability in the freshwater (FW) storage the FW budget may at any given time not balance and FW pulses can be released in association with changes in climate regimes (Proshutinsky et al., 2009). Arctic waters enter Hudson Bay from Foxe Basin via Roes Welcome Sound, a shallow passage in the northwest between the North American mainland and Southampton Island. Beyond Hudson Strait and Foxe Basin, however, there is small enough exchange of water that researchers have declared the Hudson Bay Marine Complex as a relatively closed system in regards to ocean currents and water mass exchange (Wang et al., 1994). Hudson Bay can be described as having a "double estuaries" system where freshwater comes from river input and sea ice melt. The stratification of Hudson Bay is maintained by the winter sea ice coverage formation of the ice pack – a factor that recent research suggests is spatially non-uniform over the bay (Saucier et al, 2004; Hochheim and Barber, 2010). River water inputs are primarily concentrated at the mouths of major rivers (e.g. Nelson/Hayes, La Grande, Great Whale), which form a coastal freshwater conduit feature (Granskog et al., 2009; St. Laurent et al., 2011). The freshwater coupling in Hudson Bay plays a large role in maintenance and strengthening of stratification, which in turn affects annual sea ice formation (Hochheim and Barber 2010), landfast ice thickness (Gagnon and Gough, 2006), primary productivity (Ferland et al., 2011), and higher trophic-level ecology (Dyck et al., 2007).

During the final year of this project our team focused the research activities on the Belcher Islands field program which will set the stage for the new project lead by Dr. Zou Zou Kuzyk and titled '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'. The field campaigns are described with initial analysis and results in the following sections.

Our team also completed the analysis from the field programs on board the CCGS *Radisson* and the CCGS *Amundsen*. The data from these cruises, in addition to remote data sets and re-analysis data sets was used to analyze the large, recurrent polynya in northwestern Hudson Bay. Through additional analysis we investigated the spatial, temporal, and forcing characteristics of sea ice in the area of interest and examined the winter sea ice regime and associated atmospheric and oceanographic systems.

The last focus for the final year of this project was to advance the knowledge of the impact of climate change on sea ice in Hudson Bay and the consequent risks and opportunities for shipping to and from the Port of Churchill, and the Kivalliq region of Nunavut.

ACTIVITIES

This fiscal year, April 2014 – March 2015, is the final year of the project 'Freshwater-Marine Coupling in the Hudson Bay IRIS'. As such the field programs discussed below are being transitioned into Dr. Zou Zou Kuzyk project titled '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'.

During winter 2014, there was an initial field program in the Belcher Islands. Oceanographic conditions were obtained through a community-driven research collaboration involving scientists, the Arctic Eider Society and the community of Sanikiluaq. Several excursions from January-March retrieved water samples, ice cores and CTD (Conductivity, temperature, Depth) data at several sites along the coast. A mooring with several CT's and an ADCP was deployed for the duration of the field season. Field procedures followed the methods used by Kuzyk et al. (2008). Subsamples from specific depths were taken for further analysis of Salinity, $\delta^{18}O$, and CDOM (coloured dissolved organic matter). Deployment of a CTD through landfast ice recorded water column's physical properties. Ice cores were extracted from the landfast ice to capture the change in surface layer composition.

During winter 2015 sampling resumed in the Belcher Islands. Two students from the University of Manitoba (Annie Eastwood and Vlad Petrusevich) went up to Sanikiluaq during mid January to work with Joel Heath of the Arctic Eider Society and local guides. They installed a mooring with a string of CTs and current meters at the southeast tip of the Belchers Islands (site SK-1, see Figure 1), together with a weather station and ice mass balance buoy, which was recovered in March 2015. Annie Eastwood also installed CTs under the ice at several other locations and she collected a suite of ~17 CTD casts and sampled the water column for dissolved oxygen 18 (DO18), sulphur, nutrients and CDOM at approximately 12 sites replicated again in February and March.

Joel Heath continued the community-supported research in Chisasibi, where he worked with locals to do a CTD transect north along the landfast ice, to the mouth of James Bay. A CTD was left with the local partners who repeated this transect several more times in February and March. Joel Heath continued this process with local partners in Kuujuarapik at locations both north and south of the town site as well as in Inukjuak and Umiujaq.

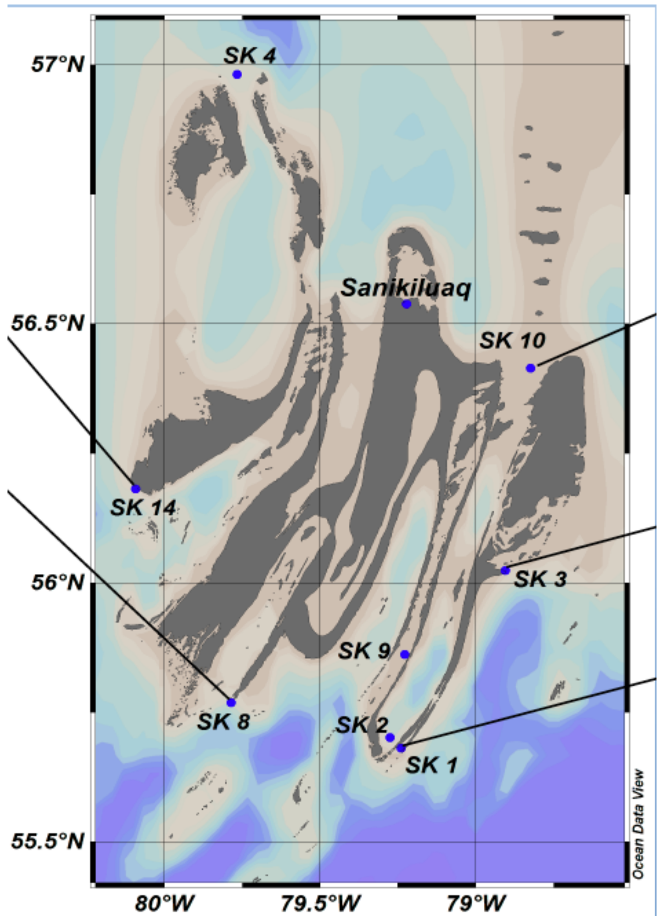


Figure 1. Map of the Belcher Islands with locations of sample sites.

Presentations and workshops

The University of Manitoba, the University of Winnipeg and the International Institute for Sustainable Development hosted a forum on Transportation Infrastructure, Climate Risks and Economic Development in the Western Hudson Bay Region on March 26th 2015 at the Winnipeg Zoo. This forum provided a unique opportunity to bring together industry, academia, community and government stakeholders to discuss emerging risks and opportunities in northern development. David Barber, David Babb, Jonathan Andrews, Zou Zou Kuzyk and Lauren Candlish were actively involved in the forum.

Dr. Greg McCullough and Zou Zou Kuzyk attended the Eeyou Marine Regional Symposium in Montreal last spring. This symposium was a venue to discuss the current issues in southeastern Hudson Bay and James Bay. Dr. McCullough gave a presentation titled “Ice and Ocean Dynamics in the Hudson Bay/James Bay Regions” and Dr. Kuzyk presented on the freshwater sources and distribution in the Hudson Bay/James Bay regions.

RESULTS

Belcher Islands field program

The Belcher Islands in southeast Hudson Bay (Figure 1) are downstream from a large input of freshwater runoff that flows northward from James Bay. This area is also known for its numerous polynyas, which play a significant role as winter habitat for birds and marine mammals. Inuit from Sanikiluaq travel and hunt in the area extensively. In recent years, concerns have been raised by local community members that the wintertime sea ice and oceanographic conditions around the Belcher Islands have undergone change. In particular, more frequent and extensive entrapment of thousands of Common Eiders during quick freeze-up events have been observed.

Results from the winter field program in 2014 are shown in Figures 2, 3 and 4 (Eastwood et al. 2014). Figures 2 and 3 show the salinity and temperature from the sites SK 14, 8, 10, 3 and 1.

To complement the CTD profiles and bottle samples, an ice-tethered mooring was installed at the southeast tip of the Belchers (site SK-1; Figure 1). Figure 4 shows the temperature and salinity time series from Jan 21 (day 21) to Mar 18 (day 77) at the mooring site (SK-1). At most sites around the southern and eastern Belcher Islands both salinity and temperature increased with depth reaching maximum values below 40 m (the bottom of the profiles).

Winter ice regime in Hudson Bay

Gunn (2015) looked into the winter ice regime in Hudson Bay. This investigation demonstrated the existence of a large coastal polynya in northwestern Hudson Bay. Measuring approximately 600 km long by 60 km wide, this polynya was typically opened and maintained by surface winds for periods of one to five days. Closing mechanisms result from decline in wind maintenance and apparent thermodynamic ice formation. Open water is present on the northwest coast at some size for up to 70% of the winter between ice formation and breakup.

Figure 5 shows data from *Amundsen* CTD casts across the MERICA transect collected July 2010 on Amundsen Leg 1a. This demonstrates different stratification across the Bay, which may be partially explained by a large and frequent polynya on the northwest coast of the Bay.

On March 17, 2010 a large, non-linear feature forced by southwesterly winds opened extending from Cape Churchill up the coast. A second polynya was apparent south of this in the Nelson Estuary, suggesting some of the forcing is due to meridional wind vectors as well as the measured zonal wind. This peak opening, 13,867 km^2 measured open water extent, demonstrates little transitional ice concentration values and a clear boundary between the nearly consolidated central ice pack and the open water adjacent to the coast. Figure 6 shows the impact of this rapid cooling on the open water area. Thermodynamic forces, in this instance, appear to rapidly produce frazil ice on the affected area. The PMW demonstrates sensitivity to young ice as increasing SIC. By March 23 – six days after the open water maximum – the northwestern study polygon will report zero open water. NARR gridded zonal winds do not report any negative values in this time period, demonstrating the polynya closing is thermodynamically-forced.

Annual sea ice extents maxima in Hudson Bay range from 4,726 km^2 (2008/2009) to 13,867 km^2

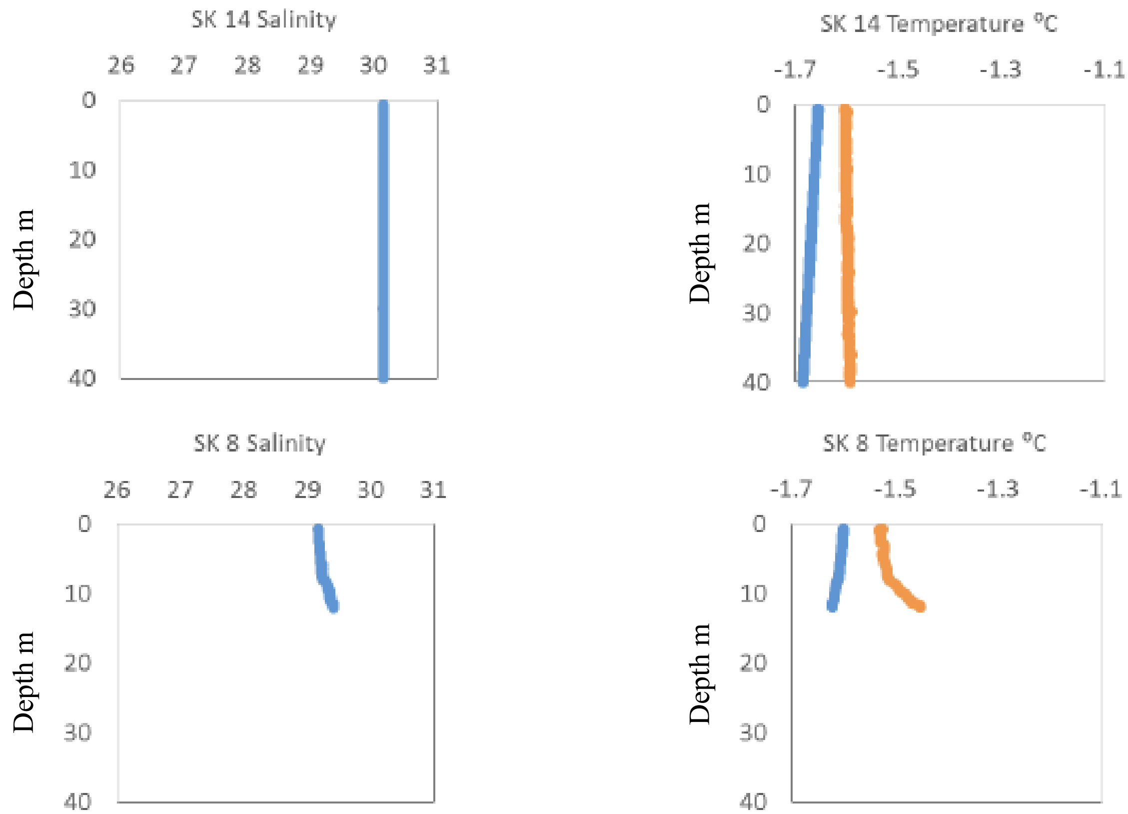


Figure 2. Plots of salinity and temperature for locations on the west side of the Belcher Islands, SK 14 and SK 8. (See locations on Figure 1.) Comparisons of the freezing point are also shown in the right hand column. Temperature as measured is shown in orange and the calculated freezing point based on salinity is shown in blue.

(2009/2010), indicating a significant amount of interannual variability. Small open water extent values near the minimum mapping unit skewed the data towards the low end, however examination with sea ice concentration data demonstrates spatial features consistent with weak or small polynyas. The conservative threshold (15%) does not account for the full polynya size (i.e. total disturbed area); although it does create a distinction between periods with significant open water and brief openings. Individual observations indicate an ice margin that ranges from a distinct edge to a highly-fractured zone of marginal ice, with leads reaching deep into the pack.

Typical length of opening is a 1-5 days with a defined peak (e.g. December 30, 2009); however there are instances during which polynya maintenance mechanisms keep a relatively constant size for up to 5 days (January 20-25, 2008). Polynya opening and closing are on similarly rapid time scales.

Port of Churchill Vulnerabilities

In consultation with Manitoba Infrastructure and Transportation (MIT), Churchill Gateway Development Corporation (CGDC), OmniTRAX and the Town of Churchill, the University of Manitoba has created a vulnerability assessment of the Port of Churchill. This study was intended to advance the knowledge of the impact of climate change on sea ice in Hudson Bay and the consequent risks and opportunities for shipping to and from the Port of Churchill, and the Kivalliq region of Nunavut. The

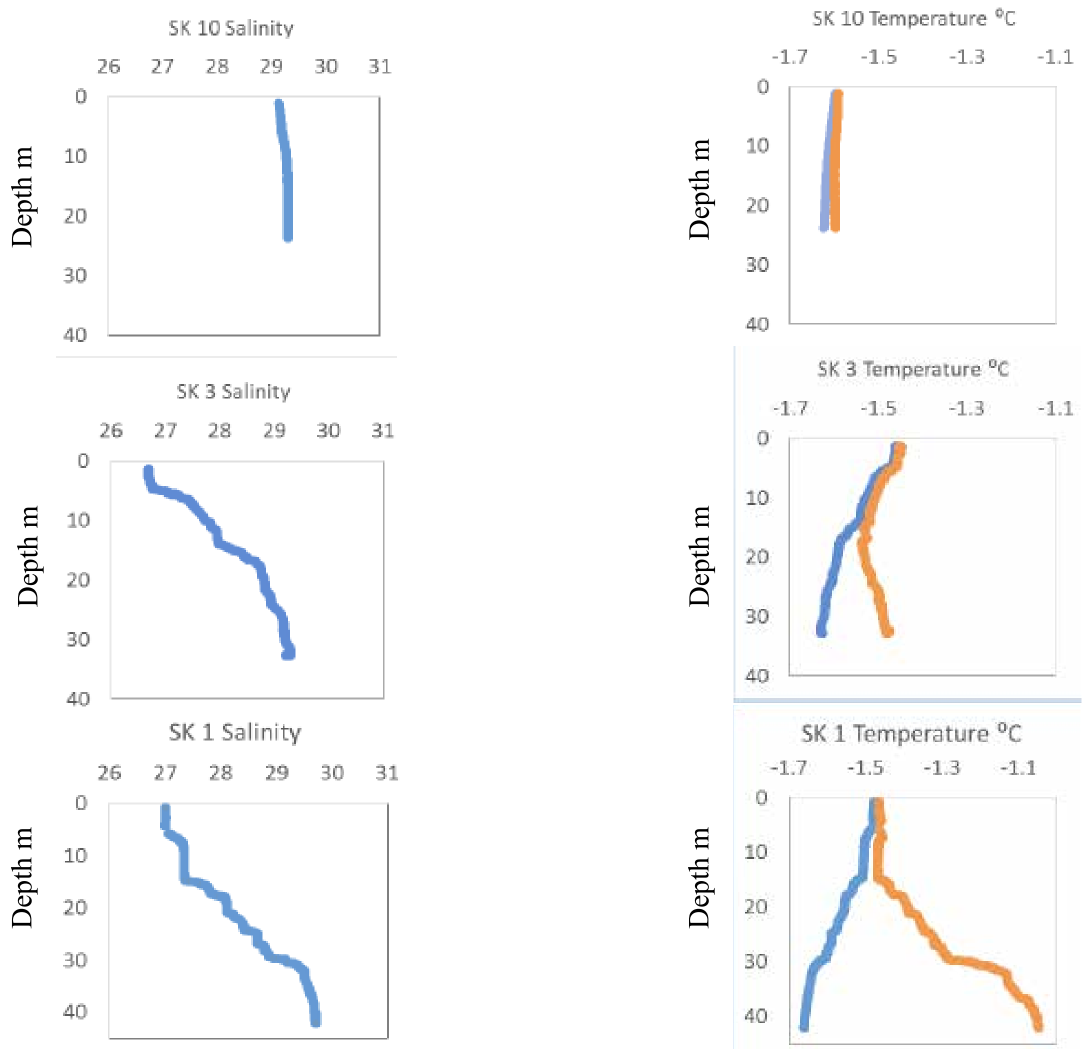


Figure 3. Similar to figure 2, for locations on the east side of the Belcher Islands - SK 10, 3 and 1.

report was designed to develop an understanding of the factors and drivers of change in the sector and region and to describe possible future atmospheric, oceanographic and sea ice conditions based on climatic scenarios.

The Port of Churchill has a shipping season of 14 weeks, from July 15th to October 31st. Between 2009 and 2014, the grain shipping season typically ran from early August to late October and averaged 11.2 weeks in length. The earliest grain shipment during this time took place on July 28th, 2010, while the latest grain shipment left the Port of Churchill on November 2nd, 2014. The re-supply shipping destined for Nunavut falls within roughly the same time frame, though the first re-supply vessel often leaves the port one or two weeks before the first grain vessel [personal communication Jeff McEachern, CGDC]. In 2014, four Sealink re-supply vessels reached Churchill, with the first arriving on July 18th and the last departing on October 19th.

The climate means, trends and projects were mainly based on Hoccheim and Barber (2014) and the NEMO model results from 2013, which were both described in the 2013 annual report. In this section we will only discuss updated and new results.

Air temperatures averages, means and trends over Hudson Bay, Foxe Basin and Hudson Strait were calculated from NCEP reanalysis data shown in Figure 7. Seasonal trends for the air temperature are shown in Table 1.

As can be seen in Figure 7 and Table 1, NCEP reanalysis data suggests that each area of the Hudson Bay System exhibits seasonal warming trends between 1979 and 2010. The data indicates 9 out of a possible 12 seasonal warming trends: summer and fall for Hudson Bay; spring, summer, and fall for Hudson Strait; and all four seasons for Foxe Basin. The entire system displays warming trends for summer and fall, and warming is most rapid in the fall in each area.

DISCUSSION

Belcher Islands field program

Figure 4 (results section) shows the presence of relatively fresh (S=26-27) surface waters in the first 7 days of the deployment and a second episode of surface freshening (S~28) in late February and early March, which are related to circulation of river runoff

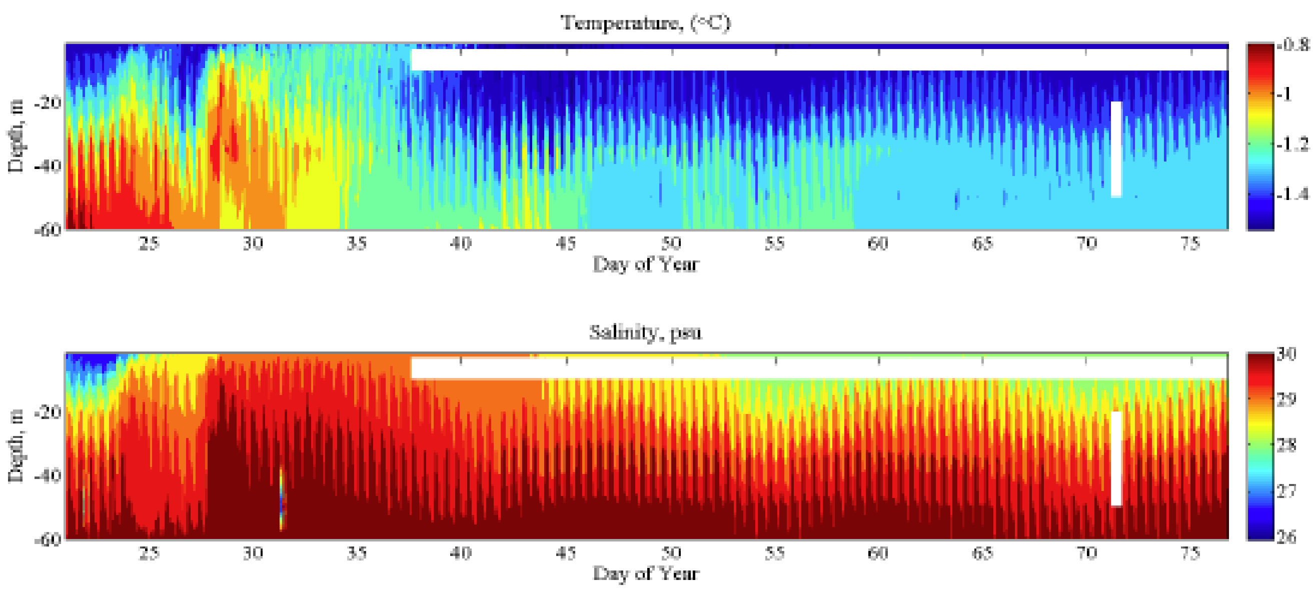


Figure 4. CT time series at mooring site SK 1, with a starting date of Jan 21st(day 21) until Mar 18th(day 77) 2014.

Table 1. The temperature trends (°C/year) from NCEP reanalysis data for the Hudson Bay System from 1979 to 2013 for each season, winter (JFM or Jan-Feb-March), spring (AMJ), summer (JAS), and fall (OND). Significant trends, computed with 95% confidence levels, are indicated with an asterisk (*).

	JFM	AMJ	JAS	OND
Hudson Bay	0.07	0.04	0.06*	0.14*
Hudson Strait	0.08	0.06*	0.05*	0.18*
Foxe Basin	0.10*	0.07*	0.05*	0.16*

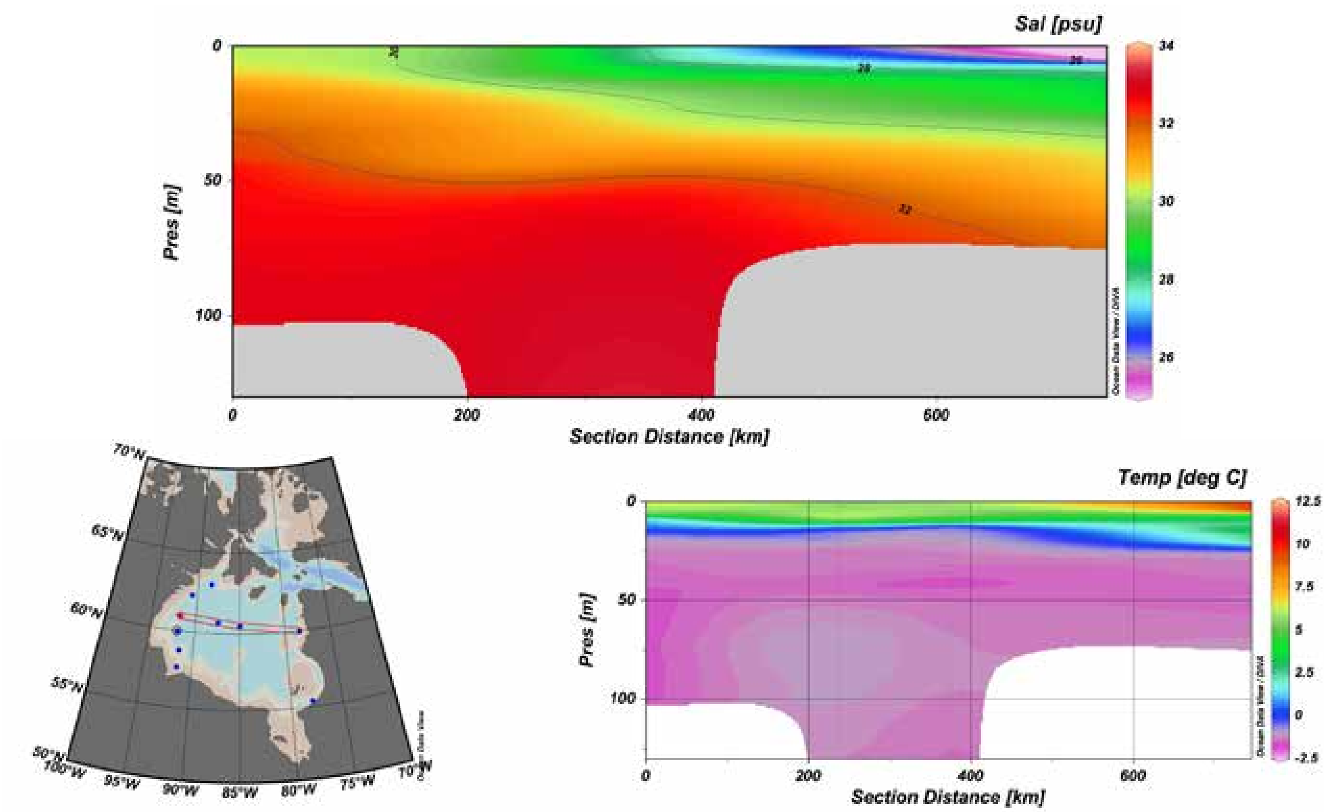


Figure 5. Salinity/Temperature cross-section from ArcticNet 2010 Cruise 1a - July 2010.

in this region. Surface water temperatures were near the freezing point initially, warmed for a period during late January-early February, then cooled again. The mooring also recorded tidally-driven oscillations of temperature and salinity through the whole water column. There are two possible mechanisms for such oscillations: 1) vertical shifts caused by internal waves or 2) horizontal shifts caused by advection of a warmer and saltier front, generating oscillations of temperature and salinity during the tidal cycle. Further research including CTD transects near the mooring location will improve our understanding of the causes of the observed episodic changes and the mechanisms underlying the temperature and salinity oscillations.

The general trends in salinity and temperature during winter 2014 showed that there was a pronounced spatial gradient. There was higher salinity along the west coast than the east, which also increased from south to north. Figure 8 shows the spatial gradient in salinity from west to east (stations SK-14 and SK-10). The gradient exited for both surface and subsurface waters.

Oxygen isotope measurements ($\delta^{18}O$) together with salinity are used in Arctic marine systems to distinguish between river runoff and sea ice melt, which is the other major source of freshwater (Ostlundand Hut, 1984; Macdonald, 2000). River water is isotopicallylight compared to seawater and the ice formed from it. The average $\delta^{18}O$ value for rivers discharging into James Bay has been estimated previously at -13 ‰ based on data collected during the summer months at the mouth of James Bay (Granskoget al., 2011).

In Figure 9a the Belcher Islands Jan-Mar 2014 data are plotted against $\delta^{18}O$-S data collected throughout

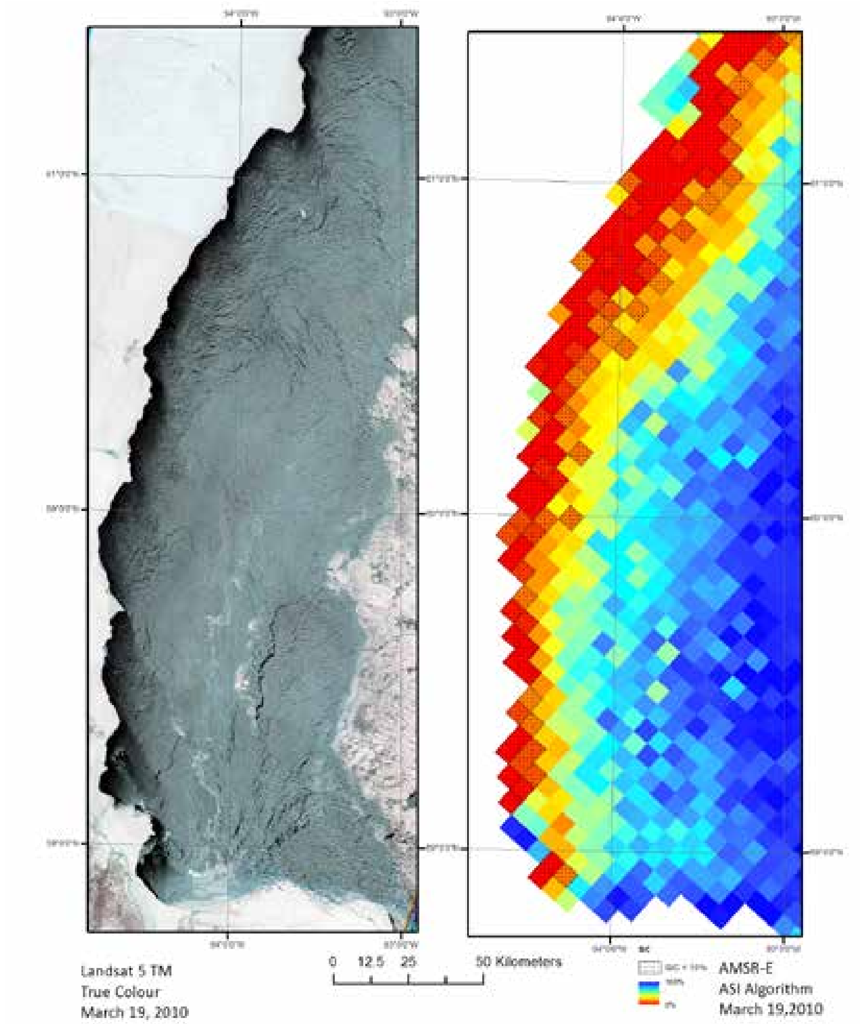


Figure 6. Same day comparison between Landsat True Colour and AMSR-E ASI sea ice concentration demonstrating a large polynya feature. Note that the AMSR-E underestimates the rapidly-freezing 'post-polynya' characterized by thin ice.

Hudson Bay in October 2005. The overall position of the Belcher Islands data indicates there is more brine in the water column. After selecting the appropriate end-members, we will use this data to quantify the amount of ice produced during winter in this major ice-forming region.

In Figure 9b the Belcher Islands Jan-Mar 2014 data are plotted by station. The lower salinity and $\delta^{18}O$ values at the southeast stations (SK-1, SK-2, SK-3) confirm that there is influence of river runoff in that region, compared to stations in the north or west.

Winter ice regime in Hudson Bay

Thinner ice at the margin of a greater ice pack also has weaker strength, increasing susceptibility to ridging, rafting, and divergence. During frazil ice formation Langmuir rolls may be formed parallel to wind direction, further altering ice volume distribution in the polynya region. This is a pattern typical to late-season CIS charts data analyzed within the study period, adding support to the research hypothesis that the site of the northwestern polynya contributes significantly to ice production in the bay (Saucier et al., 2004). Significant ice production

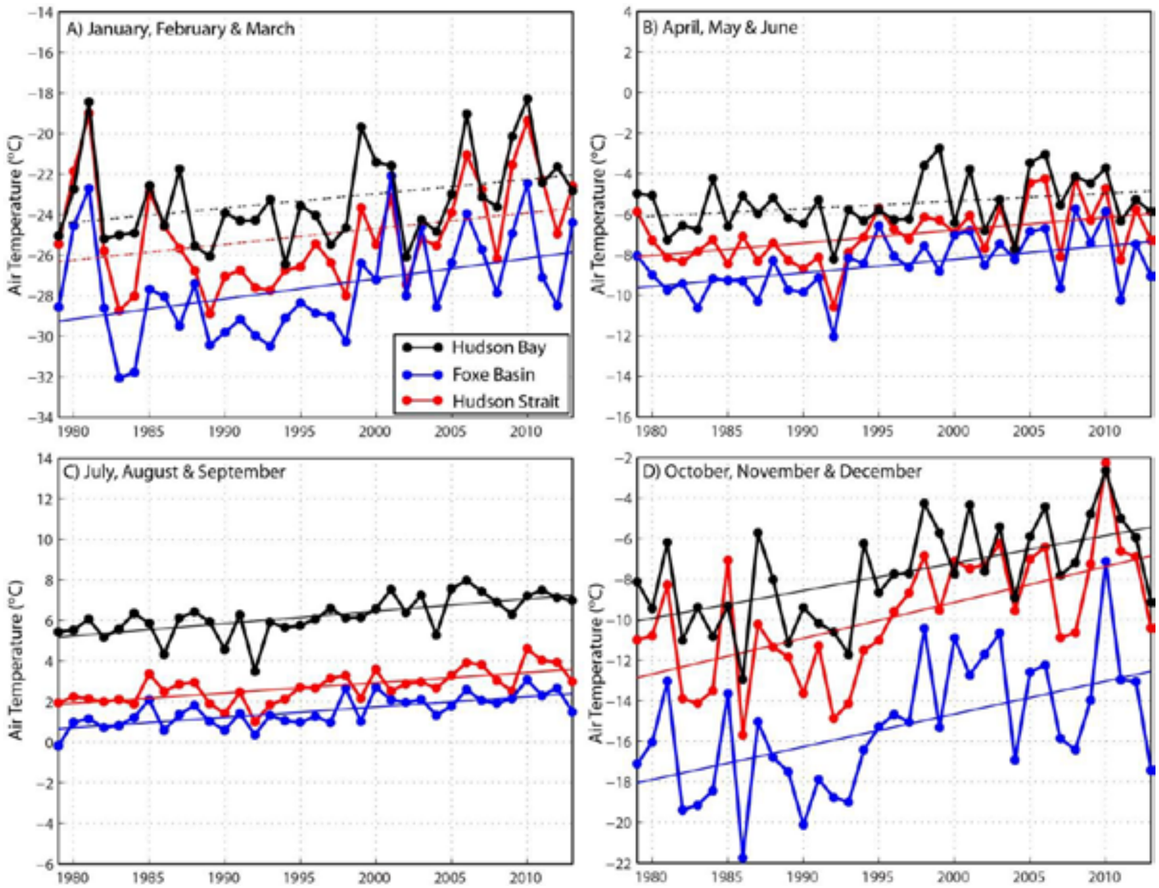


Figure 7. The seasonal air temperatures for Hudson Bay (black), Foxe Basin (blue), and Hudson Strait (red), for 1979 to 2010. Trends are indicated with a solid or dotted line, where solid lines indicate significant trends.

induces gravity mixing, and when it is localized over a small portion of the bay this may be a site of significant bottom water formation. Bay wide circulation reported in the literature as dominantly cyclonic would circulate this watermass at depth (Prinsenberg, 1986).

The polynya may also condition water in regards to sea surface temperature (SST). Galbraith and Larouche (2011) found a positive relationship between earlier spring breakup dates, surface air temperature anomalies, and warmer maximum summer SST. Their subregion #18, along the northwest coast, demonstrated consistently low SST during the warmest week of each year. Conceptually the findings presented suggest that a longer period of incoming solar radiation may precondition the water, warming the low-albedo water mass faster than the surrounding icescape. The lack of high SST in the northwest suggests other factors, such as surface air temperature or upwelling of cooler water, may also affect stratification in this region.

Figure 5 (results section) showed CTD data collected on ArcticNet Leg 1a in July 2010 along the MERICA transect. A much thinner western summer mixed layer consistent with this conditioning hypothesis can be seen in the salinity data, while a temperature cross-section demonstrates more consistent temperature stratification across the bay. Ice production and resultant brine drainage and gravity mixing may

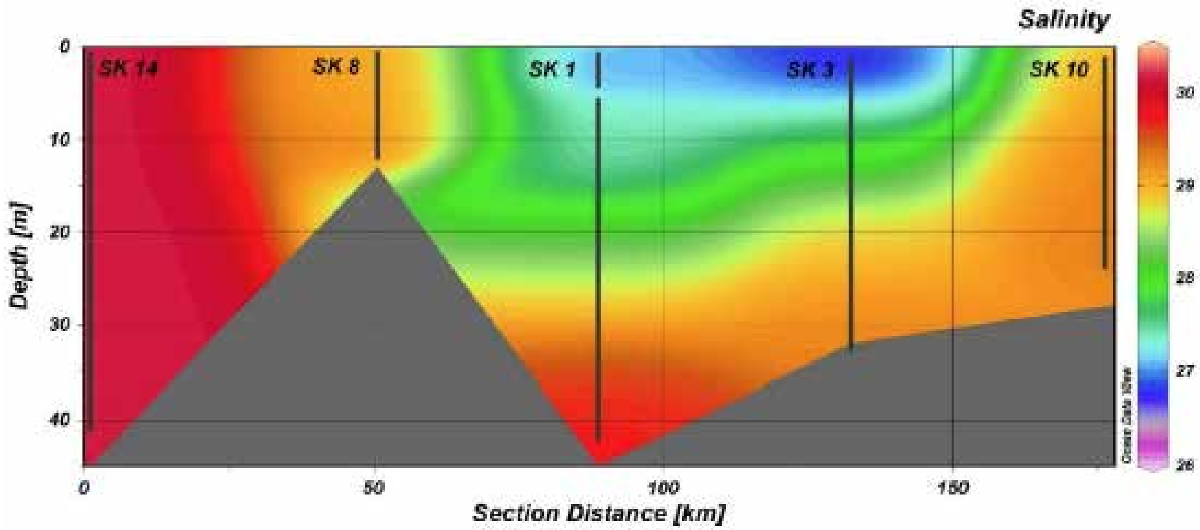


Figure 8. Extrapolated general trend between southern sample sites of the Belcher Islands.

contribute to the lower stratification in this region in addition to other causal factors (i.e. inbound Arctic water via Roes Welcome Sound, upwelling water masses, tidal mixing, winter conditioning due to brine rejection and gravity mixing, a thinner freshwater layer from melted sea ice, and northwestern river water input).

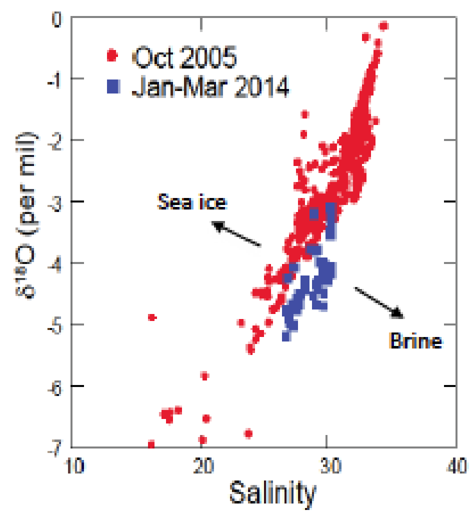
The polynya in northwestern Hudson Bay likely affects biota from autotrophs to pinnacle carnivores. The icescape of the region is an important habitat for the western Hudson Bay polar bears; a solid barrier to air for overwintering marine mammals; and a growth medium for ice algae and pelagic phytoplankton.

Port of Churchill Vulnerabilities

It is known that the climate in Hudson Bay is warming and the sea ice in this region is climate driven. It has been shown in numerous studies that the changes seen in the sea ice trends, specifically during the formation and breakup periods, are directly related to the warming (Etkin 1991, Hochheim and Barber, 2014). Further, numerous global circulation models (GCMs) predict further warming in this area, especially during the October to April time period, a key contributor to spring thaw. Despite consensus between ocean ice models that there will be extension of the ice-free season and decreases in sea ice thickness with maximum reductions following the southeast to northwest gradient in Hudson Bay, differences in estimated thickness values exist between models (Joly et al., 2011).

We can project with high confidence that the open water season will lengthen by a month or more over the next 30 years, but there are remaining uncertainties for an assessment of ice hazards, forecasts, and infrastructure operations in shipping and navigation.

With the extension of the open water season there will be an increase in shipping season length to the Port of Churchill. Ships entering Hudson Bay through the open water route to Churchill pose less concern to coastal species. However, of more concern would be the general disruption of sea ice for marine mammals if ice breaking activity were to occur. Erbe and Farmer (2000) estimated the zone of behavioural disturbance for icebreakers for beluga whales could be up to 32 km for bubblers (which aid in clearing ice from the vessel's path) and up 46 km for icebreakers. In a recent assessment looking at large-scale mining developments such as Mary River, it was observed that shipping routes largely overlap or



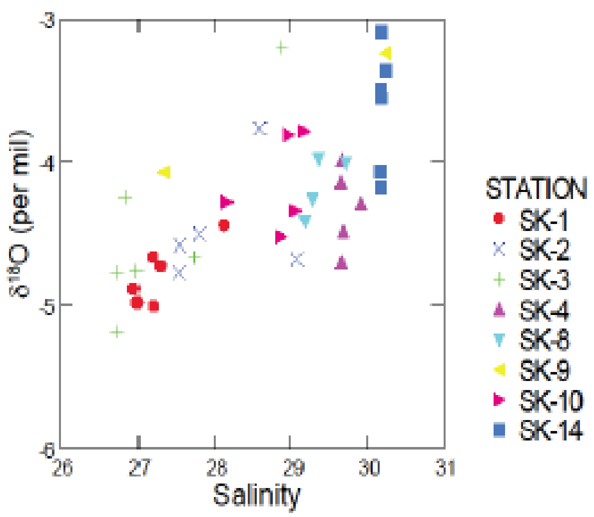


Figure 9. 9a (top) and 9b (bottom) shows the comparison between the Belcher Islands and Hudson Bay's $\delta^{18}O$ *values.*

will overlap with areas of core use for many cetacean species, especially during winter when open water areas and ice leads provide the only habitat available (Lawson and Lesage, 2013). In absence of alternative habitat, it has been documented that displaced marine mammals or individuals exposed to anthropogenic noise, could display temporary or persistent physiological (i.e., stress) and behavioural responses (Stafford 2013).

With a lengthened open water season, conditions that lead to fog and freezing precipitation, specifically the contrast in land and sea temperature, may increase in Fall while heat held in the ocean waters dissipates. While the theoretical basis for this is sound, reliable projections for fog and freezing precipitation are not available, and thus there cannot be a statement on the impact of future operations from the Port of Churchill.

While enhanced variability in summer surface winds due to changes in cyclonic and storm activity will have implications for shipping and navigation in the Hudson Bay region, there is a limited basis to project that the currently observed small trends will change in the future. There is no indication that extreme events have changed, or will change sufficiently to positively or negatively impact operations.

CONCLUSION

Gunn (2015) demonstrated the existence and spatial-temporal characteristics of a polynya in northwestern Hudson Bay and explored the greater coastal polynya system during winter months. A large, recurring area of open water exists along the northwestern coastline from Churchill, MB to the mouth of Roes Welcome Sound extending from the fast ice margin to a variable distance offshore. This area displays the recurrent spatial character of a coastal polynya, rather than variable nature of a shore lead. The primary forcing mechanism of this polynya appears to be persistent westerly winds forced by either a frequent trough between cold Arctic air and cool midlatitude air, or a Baffin Island low pressure system. Maintenance of the polynya may be warmer winds from the southwest, however the balance between dynamic momentum transfer and thermodynamic heat loss can be very fine as demonstrated in the case study. This suggests considerable ice production localized to the study area, causing cascading effects to the greater marine system. Physical effects may include considerable brine rejection and associated lessened stratification, weakened ice strength, and increased solar radiation inputs. No change was noted over the eight season study period in size or frequency of this polynya during the winter. Given the history of rapid change in the climate and sea ice regime of Hudson Bay, continuous observation is a requirement for reasonable management of this ecosystem.

The 2014 and 2015 winter campaigns in the Belcher Islands is the transition to Dr. Kuzyk's project titled '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'. The new project will continue to document the spatial patterns, seasonal evolution and inter-annual variability in freshwater distribution in winter in the coastal corridor in southeast Hudson Bay. It will also continue to 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.

The Churchill Vulnerability Assessment will directly tie into the Hudson Bay IRIS. This report has laid the groundwork for the climate of Hudson Bay and for the chapter currently titled "Transportation in a Changing Climate".

Our project has established baseline data that characterizes Hudson Bay. This year alone we have produced 17 publications, with more to be submitted early in the next fiscal year. We have been able to document the changes over the past decade and through this we can now look at the implications of these changes in the near future.

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IMPACTS OF GLOBAL WARMING ON ARCTIC MARINE MAMMALS

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ABSTRACT

This project examines various aspects of Arctic marine mammal (seals, whales, and polar bears) ecology to try to determine the impacts of global warming on their abundance and distribution. Research will answer: 1) How will marine mammals adapt to global warming and what are the possibilities for future survival? 2) What is the relationship between warming temperatures and the habitats of seals, whales, and polar bears? 3) What are the potential effects of global warming on reproduction and survival? 4)What will be the effects of changes on northern communities and Inuit lifestyle? 5) How can we reduce the impacts of these changes on Arctic peoples and marine mammals? Satellite tracking, analysis of tissue samples collected by local hunters, and genetics and population modeling are methods that will be used to understand how these animal populations may respond to environmental change. Several areas of Arctic marine mammal health are also being studied, including diet, diseases, contaminants, and stress. Knowing how polar ecosystems may change with global warming will help to develop strategies for conservation and species management. Northerners depend on these species as a food source and as an integral part of their unique culture, and results will help Inuit communities adapt to changes in marine mammal distribution and abundance.

KEY MESSAGES

- Average global temperatures are predicted to increase over the next century. Temperature increases are expected to be most intense in polar regions, and recent evidence shows the Arctic climate is already warming.
- Sea ice reductions resulting from climate warming will considerably alter Arctic marine ecosystem structure and function.
- Arctic marine mammals (seals, whales, and polar bears) are vulnerable to changes in their environment through direct impacts such as habitat loss (for example, sea ice as a platform for hunting or giving birth) and indirect impacts, such as changes in prey abundance.
- We are using an integrated ecosystem-based approach to study the effects of climate warming on Arctic marine mammals. This involves research on marine mammal diet and food web structure, seasonal movement patterns and migration, reproduction and population structure, and ecosystem modelling.
- Arctic marine mammals are culturally and economically important for Northerners, and understanding links between their ecology and physical environment will help to develop adaptive conservation and management programs as their abundance and distribution change in a warming Arctic

OBJECTIVES

- Study coupling between physical environment (e.g. sea ice dynamics) and marine mammal abundance, distribution, and population structure.
- Use chemical signals (stable isotopes, fatty acids, and contaminants) to study Arctic marine food web structure and marine mammal diet responses to environmental changes.
- Conduct satellite telemetry, chemical analysis of tissues, and modelling studies to understand marine mammal movements and migration in response to seasonal changes in their environment.
- Study emergent ecological responses such as disease and invasion by competitors or predators.
- Conduct species-level extinction risk analysis.
- Build community-based monitoring programs that provide marine mammal and food web tissues for lab-based analyses.
- Build ecosystem models encompassing biological and environmental variables to predict whole-ecosystem responses under future climate scenarios; model effects of non-linear changes such as predation and regime shifts.
- Develop adaptation strategies to mitigate effects on Northerners who are dependent on Arctic marine mammals as a cultural and economic resource.

INTRODUCTION

Our research investigates impacts of global warming on Arctic marine mammals and development of adaptation strategies to mitigate these effects on Northerners. In the Arctic, where climate warming is already occurring, changes in sea ice cover will considerably alter Arctic marine ecosystem structure and function. Arctic marine mammals (seals, whales, and polar bears) are vulnerable to these changes in their environment through direct impacts such as habitat loss (for example, sea ice as a platform for hunting or giving birth) and indirect impacts, such as changes in prey abundance. We predict shifts in climate and oceanographic processes affecting sea ice will impact food webs, diseases, contaminants, competition, and predation, ultimately resulting in changes in Arctic marine mammal distribution and abundance.

The central emphasis of this project is to study the coupling between physical environments, particularly sea ice dynamics, and marine mammal population demography to better understand how Arctic marine systems will respond to global warming. We are collecting detailed empirical information throughout Canadian Arctic marine ecosystems using both scientific and traditional ecological knowledge to quantify changes in Arctic marine mammal reproductive success, condition, and survival. Research will incorporate community-based monitoring to collect samples and engage Northerners in developing their science, and focuses on all Arctic marine mammals (ringed and bearded seals, walrus, beluga, narwhal, bowhead, killer whales, and polar bears).

Links between key ecological components of the study will be integrated using chemical analytical methods (e.g., stable isotope and fatty acid profiles to infer food web structure, contaminants analysis to track pollution), satellite telemetry to study fine-scale habitat use and broad movement patterns/distribution, and genetics profiling to determine group and population structure. Emergent ecological responses such as disease and invasion by competitors and predators will also be studied. Ultimately, statistical and mathematical models will be used to integrate data on focal species with climate, oceanography, and sea-ice data to identify sensitivities of species to particular habitat variables. These relationships will then be used to quantify the direction and species-specific consequences of regime shifts and other ecosystem changes.

Our results will help to develop adaptive conservation and management programs for marine mammals as their distributions and abundances change, which will also benefit Northerners who are culturally and economically reliant on these species. Success will require community support and participation throughout Alaska, Inuvialuit, Nunavut, Manitoba, Ontario, Quebec, Nunavik, Nunatsiavut, and Greenland. Project activities include training and engaging Northern communities as an extended network of on-site collaborators through incorporation of northern students and hunters into our programs in the field and in the laboratory. These collaborations will facilitate knowledge transfer and contribute to building science capacity in the North. Our project provides a unique opportunity to link rigorous scientific methodologies with traditional ecological knowledge to advance an integrated view of climate change and its impacts on Arctic marine ecosystems.

ACTIVITIES

Seals

- Stable isotope data from ringed seal liver and muscle samples from across the Arctic were analyzed, as well as satellite telemetry data from several communities in Nunavut (Resolute, Ulukhaktok, Igloolik, Sanikiluaq, Saglek Bay) and Greenland (Melville Bay).
- Samples of ringed seal tissues were collected from the communities of Arviat, Sanikiluaq, Resolute, Kugaaruk, and Gjoa Haven as part of a community based sample collection program.
- Western Hudson Bay ringed seal aerial survey data, for surveys conducted between 1995 and 2013, were analysed to assess trends in population density.
- In partnership with the Government of Nunavut, more than 200 ringed seal pelt samples were collected from eight Nunavut communities (Arviat, Pond Inlet, Pangnirtung, Grise Fiord, Cape Dorset, Kugaaruk, Qikiqtarjuaq and Gjoa Haven). Samples will be used for studies of contaminants in ringed seals and of ringed seal population genetics.

Beluga, Narwhal, Bowhead, and Killer Whales

- Beluga whale samples (spleen mass, blood and muscle) were taken at Kendall Island, Northwest Territories in July 2014. Sampled tissue will be analyzed for hemoglobin, hematocrit, and myoglobin as indicators of beluga health and energetics.

- Habitat use by beluga whales in the Beaufort Sea was investigated to enhance our knowledge of spring arrival and distribution. Data from 2012 and 2013 aerial surveys will be used to examine (1) beluga habitat use of sea ice, bathymetry and freshwater flow from the Mackenzie River; (2) identify beluga preference of ice edge versus open water environments; and (3) assess the selection of these features as it relates to the progression of sea ice break-up along the shelf.
- An aerial survey of beluga whales in Cumberland Sound was conducted in August 2014 to obtain an updated population estimate and to assess trends in abundance.
- Analysis of beluga and narwhal reproductive tracts, mating systems, and diet.
- Narwhal social structure was investigated by comparing dietary and genetic signatures, and dive behaviour was analyzed of narwhal from Baffin Bay, East Greenland and northern Hudson Bay.
- From the Pangnirtung bowhead whale hunt in August 2014, samples were collected including lean tissue, blubber, feces and baleen. Samples will be used to estimate foraging efficiency (baleen) and energetic values (remaining tissue) for bowhead whales to predict mean daily bowhead whale energy requirements.
- Zooplankton samples were collected in Pangnirtung and Kingnait Fjords (Cumberland Sound) in August 2014 in the proximity of bowhead whales. The samples will be used to determine bowhead whales' primary prey, how energetically rich prey organisms are, and where in the water column prey were most concentrated.
- Bowhead whales exhibiting foraging behaviour in Cumberland Sound were equipped with short-term dermal tags with a time-depth recorder. The data collected will be used to reconstruct the spatial movements of tagged bowhead whales.
- To assess alternative seasonal foraging hypothesis (winter fasting versus year-round foraging), stable nitrogen, carbon and sulphur isotope compositions were measured along continuously growing baleen plates from bowhead whales of the Eastern Canada-West Greenland population.
- Three communities in the eastern Canadian Arctic were visited by researchers in July and August 2014 to collect killer whale samples (biopsies, photographs) and attach satellite transmitters. Teams of Northerners were equipped and trained in the use of killer whale sampling equipment to establish a killer whale community-based monitoring program across the eastern Canadian Arctic.
- Bulk and amino acid specific isotopic composition of dentinal collagen in teeth of 13 killer whales from the eastern Canadian Arctic and Northwest Atlantic were analysed to assess the degree of dietary specialization of killer whales in eastern Arctic and northwest Atlantic.
- An investigation of anti-predator behaviours exhibited by bowhead whales and narwhal in the presence of killer whales was initiated using satellite telemetry data from 2009 (all three species) and 2013 (bowhead and killer whales) to reveal the intimidation effects of killer whales to prey. When predators are present, prey may alter their behaviours to avoid predation, carrying consequences that may be costly for overall prey population survival (Pressier et al. 2005).

Polar Bears

Polar bears were caught as part of a population monitoring study, to obtain tissue samples, estimate population size, and to deploy GPS collars. Field research was conducted in the Viscount Melville Sound population in spring 2014 in cooperation with NWT Environment and Natural Resources (Inuvik) and Environment Canada. Field operations were based in Aulavik National Park.

Field research was conducted in August-September 2014 in the Western Hudson Bay populations to deploy GPS satellite collars and to continue the long-term population demographics study. This study was conducted in cooperation with Environment Canada.

Ecosystem

- The construction of an ecosystem model for the Beaufort Sea shelf was completed to identify food web structure. The model has been fit to historical data (1970-2012) in order to stimulate past changes and identify key stressors such as harvest and climate change in the ecosystem.

RESULTS

Seals

The $\delta^{13}C$ and $\delta^{15}N$ values for ringed seals remained unchanged between 1990 and 2011 for much of the Arctic. Ringed seals of both subadult and adult age-classes mainly consumed pelagic forage fish, albeit in lower quantities for subadults and underwent moderate ontogenetic niche shifts. Our findings varied between locations, where ringed seals from the high-Arctic mainly foraged on Arctic Cod (i.e. Resolute) and benthically (i.e. Ulukhaktok) compared to lower latitudes where higher consumption of invertebrates occurred (i.e. Chesterfield Inlet and Saglek Bay).

There are substantial differences in movements across the Arctic with ringed seals captured in Resolute mainly traveling extensive distances where seals from other areas mainly reside in areas near their capture locations. Overall, the degree of spatial and temporal variation in diet, habitat use and behaviour illustrate dietary plasticity as a species suggesting adaptability to climate change.

Analysis of aerial surveys of ringed seals in western Hudson Bay, conducted between 1995 and 2013, revealed variation in ringed seal density estimates ranging from 1.22 seals/km^2 in 1995, to 0.20 seals/km^2 in 2013. Density estimates varied significantly over the study period and, with the exception of 2013, appeared to follow a cyclical pattern. Although density estimates also appear to follow a downward trend over time, results of multiple linear regression, weighted by survey effort, indicated no significant trend in ringed seal density as a function of year, survey date, or proportion of open water. In addition, no significant correlation was observed among any of the environmental variables and density estimates (Young et al. in press).

Analysis of aerial survey photographs of western Hudson Bay ringed seal surveys in 2009 and 2010, indicated that ringed seals hauled out on the ice would dive in response to the survey aircraft, before being available to be seen by visual observers, 8 to 9% of the time. In general, analysis of aerial survey photographs resulted in higher density estimates than those obtained by visual observers using traditional survey techniques.

Beluga, Narwhal, Bowhead, and Killer Whales

Investigation into beluga habitat use in the Beaufort Sea and Mackenzie Estuary indicates that in 2012 and 2013 beluga were found in open water to light ice concentrations. In 2013, medium ice conditions were selected less than expected. A preference for medium floes was observed in both years. Beluga were found in 0-50 m depth significantly more than expected in both years and also found more than expected closer to the ice edge than in offshore environments. Beluga were found in medium to high turbidity areas more than expected and were increasingly found in high turbid areas as dates move closer to breakup in 2012.

The results of Multiple Correspondence Analysis (MCA) highlight the significance of specific habitat classes where belugas are repeatedly found before breakup. For example in 2012, Shallow Bay found a high density of beluga and is more associated with habitats of medium ice concentration, large floes, high turbidity and 0-100 m depths. In 2013: medium-heavy ice conditions, medium-large floes, 50-100 m depth and low turbidity were most associated with beluga observations in Kugmallit Bay and the Tuk. Peninsula. These ‘high use’ areas, such as Shallow Bay, are also vital to beluga during the summer months.

Analysis of beluga and narwhal reproductive tracts revealed that belugas have larger testes relative to body size than narwhal, indicating higher levels of sperm competition in beluga. Beluga testes masses varied throughout the year, with the greatest masses in spring. Hudson Bay beluga had the largest testes of all beluga populations studied in the Canadian Arctic. Narwhal testes size is correlated with tusk length, indicating the tusk is an honest advertisement of male virility. (Kelley et al., 2014a). Teste mass and sexual size dimorphism are inversely related in odontocetes. Odontocetes follow the same pattern of evolutionary trade-off between investment in testes and investment in male body mass as other mammals. Brain size is correlated with increasing testes mass, indicating a potential for increased intelligence with increased polygynandry (Kelley et al., 2014b).

Hudson Bay belugas have diets that are more sea-ice associated in spring when compared to summer. Diet biomarkers suggest that beluga may be feeding in the estuary plume during the summer (Kelley 2014). Narwhal show sexual segregation in feeding behaviour, while beluga do not. This may be related to a more polygynous mating system in narwhal where males and females segregate outside of the mating season, while in the more promiscuous beluga, males and females associate year round (Kelley 2014).

In a study of bowhead feeding and dive behaviour, a total of 31 zooplankton samples were collected from Kingnait Fiord (n=27) and Pangnirtung Fiord (n=4) in 2014. Of those samples collected in Kingnait Fiord, 6 were collected at the interpreted maximum dive depth of a tagged bowhead whale and 4 were collected in close proximity to where a tagged whale was traveling in shallow water and close to shore. Four bowhead whales were tagged with the short-term archival tag (Table 1). All tagged individuals appeared to demonstrate an anti-predator response such that they would swim along the shoreline in shallow water for a minimum of 15 mins and a maximum of 1.5 hrs following tagging.

Stable isotope analysis along continuously growing baleen plates of bowhead whales indicated synchronous nitrogen and carbon cycles, with periods

Table 1. Summary table of all bowhead whales tagged in Kingnait Fiord, NU.

Number	Date	Tag duration	# of prey samples	Notes
TDR001	08/13/2014	8 hours	6	Increased freshwater input due to several days of consecutive rain may have slowed down the corrosion of the zinc foil.
TDR002	08/20/2014	41 minutes	0	Whale broke tag off presumably by rubbing against a large boulder while traveling close to shore.
TDR003	08/21/2014	14 minutes	0	Zinc foil corroded prematurely likely because of the large hole in the zinc foil and the fully corroded end cap.
TDR004	08/21/2014	1 hour and 26 minutes	4	Tag stayed on longer because only a small hole was added to the zinc foil. Only two euphausiids were found in the zooplankton samples.

of nitrogen enrichment corresponding to foraging on the summer grounds, were inconsistent with standard fasting prediction (Matthews and Ferguson 2015). However, nitrogen cycles could reflect changes in diet-tissue nitrogen discrimination between periods of intense foraging throughout the open-water season and supplemental protein intake during winter/spring. Correlations between nitrogen and sulphur values, potentially meditated through amino acid metabolism, support this interpretation. Reasonable agreement between baleen isotope oscillations and regional baseline nitrogen and carbon variation also indicated foraging occurs within isotopically distinct food webs across the summer and winter ranges.

Stable isotope analysis of dentinal collagen in teeth of 13 killer whales indicated interannual isotopic variation across growth layer groups was less than that among individuals, and median bulk nitrogen isotopic values differed by up to 5 ‰ among individuals (Matthews and Ferguson 2014). Significant correlation between bulk nitrogen values and baseline (source amino acid) nitrogen values indicated much of the observed isotopic variation among individuals reflected foraging within isotopically distinct food webs, rather than diet differences.

Polar Bears

Comparing the body size, condition, and recruitment of polar bears captured in the Chukchi and Bering Seas between two periods (1986-1994 and 2008-2011) when declines in sea ice habitat occurred revealed that geographic differences in the response of polar bears to climate change are relevant to range-wide forecasts. Home range distribution of individual polar bears in Western Hudson Bay differed between seasons and across years, with most variation during freeze-up and break-up seasons. Home range size was predicted by season, ice break-up date, and individual in a multiple regression. Solitary females had smaller home ranges and were closer to land compared to females with offspring. The sea ice population boundary often encompassed only half of the 2004–2012 polar bear locations and needs to be reassessed. The distribution of polar bears has shifted since 2004, but the consequences remain unclear due to the significant variation. Development of a new means of assessing polar bear habitat using polar bear kill sites found that weighting the habitat model with the kill data and prey biomass improved its fit.

Ecosystem

The construction of an ecosystem model for the Beaufort Sea shelf to identify food web structure allows us to synthesize information on all species to account for different players in the food web. Changes to individual species groups were identified and verified by literature and other research. Changes to individual groups may appear high (up to a doubling of biomass over time), however in the context of the ecosystem these changes are not large. Most species that have moderate changes in biomass (i.e. greater than a 20% increase or decrease in biomass from the starting 1970 value) have low contributions to the total ecosystem biomass meaning they have low impacts to total change in the ecosystem. Total ecosystem biomass has increased (slightly) over the last 40 years due to increases in primary production. This has led to increases in zooplankton and fish. However the trophic level of the ecosystem has remained constant, indicating that there is no restructuring of the ecosystem, and it has remained fairly stable over the last 40 years.

DISCUSSION

Seals

Of the carbon and nitrogen stable isotopes analyzed for ringed seals between 1990 and 2011, values remained stable despite an increase in summer sea surface temperature in one location (Pangnirtung) and a rapid rate of sea ice decline across the Arctic.

It appears that ringed seals mainly consumed pelagic forage fish, albeit in lower quantities for subadults and underwent moderate ontogenetic niche shifts. Ringed seals from the high-Arctic mainly foraged on Arctic Cod (i.e. Resolute) and benthically (i.e. Ulukhaktok) compared to lower latitudes where higher consumption of invertebrates occurred (i.e. Chesterfield Inlet and Saglek Bay). There are substantial differences in movements differences across the Arctic with ringed seals captured in Resolute mainly traveling extensive distances where seals from other areas mainly reside in areas near their capture locations. Overall, the degree of spatial and temporal variation in diet, habitat use and behaviour illustrate dietary plasticity as a species suggesting adaptability to climate change.

Analysis of western Hudson Bay ringed seal aerial surveys provide important time series data that can be incorporated into future studies involving ecosystem modelling and can be used to assess future changes in western Hudson Bay ringed seal density. Although our results do not indicate that a significant decline has occurred, the low density estimate in 2013 may be an indication that population changes, unrelated to a natural cycle, are taking place. We were unable to test for direct effects of changes in food supply or predation, but polar bears, Arctic foxes, and Inuit communities in the Hudson Bay region all would be negatively impacted should ringed seal populations undergo significant declines. Further monitoring and directed research are necessary to understand what mechanism may be responsible for the observed changes in ringed seal density.

Analysis of ringed seal aerial survey photographs suggest that the photographic methods used to survey ringed seals in western Hudson Bay provide higher density estimates than visual surveys. However, this is not always the case, as some transects had photographic density estimates that were lower than or about equal to visual density estimates. Further research is needed to fully assess the advantages and disadvantages of photographic survey methods for ringed seals. Continued study will help to identify problems with current photographic methods, and offer recommendations for improvements to photographic survey techniques, eventually leading to methods that will provide a clear advantage over traditional visual surveys.

Beluga, Narwhal, Bowhead, and Killer Whales

Beluga whales are globally being forced to respond to changes to the marine environment, most importantly those caused by climate change (Laidre et al. 2008; Huntington et al. 2007)). Habitat features of importance for beluga whale spring time arrival in the southeast Beaufort Sea appear to be sea ice conditions, along with fresh water flow from the Mackenzie River.

Stable isotope analysis in the world's three narwhal populations found they forage on different primary prey, suggesting narwhal are adaptable in their preferred prey and that there is potential for them to adjust foraging behavior in the face of changing climate. Dietary changes were also assessed over three decades to determine how sea ice changes have affected narwhal foraging for the Canadian populations. Dietary changes were evident and can be attributed to changes in sea ice patterns and an altered migratory pathway for narwhals.

Genetic relatedness and dietary signatures from fatty acids were assessed for an entrapped group of narwhals to determine if individuals that are closely related forage together, which would support a matrilineally driven social structure where females teach their young foraging strategies, and/or travel and forage together. No evidence that narwhals form a matrilineal social group was discovered. Dive differences among populations corresponded with differences in diet, suggesting that narwhals employ specialized foraging strategies.

Bowhead whale foraging behaviour, and seasonal variation in foraging behaviour was also investigated. In summer, zooplankton community structure in two fjords in Cumberland Sound differ spatially, where

Pangnirtung fjord was dominated by *Pseudocalanus* spp., and Kingnait Fjord was dominated by three *Calanus* species. Bowhead whales frequent Kingnait fjord and occur infrequently in Pangnirtung Fjord, which may indicate a predominance of *Calanus* zooplankton species in bowhead diet, at least during the summer period. To determine seasonal variation in bowhead foraging behaviour, $\delta^{15}N$ and $\delta^{34}S$ cycles were analyzed. Bowhead whales of the Eastern Canada-West Greenland population do appear to forage throughout their summer and winter distributions, however foraging during winter appeared to be reduced (Matthews and Ferguson 2015). Foraging outside of periods of peak productivity likely contributes to annual metabolic requirements and winter habitat selection.

Through examination of the descent and ascent phases of bowhead whale dive profiles in Cumberland Sound, information on body condition was obtained and results suggest that bowhead whales in this region are in good body condition. A significant blubber layer would contribute to positive buoyancy, requiring vigorous fluking during the descent phase in order to reach the bottom phase of a dive, but fewer fluke strokes would be required in ascent. Of the four bowhead whales tagged with short-term dermal tags in Cumberland Sound, fluking rates during portions of the descent were higher compared to ascent, indicative of positive buoyancy. Simon et al. (2009) also found that bowhead whale swim speed was lower during descent and higher during ascent, suggesting that the tagged whales were positively buoyant.

Longitudinal nitrogen and carbon stable isotope profiles across dentinal growth layer groups indicated consistent isotopic differences among eastern Canadian Arctic and Northwest Atlantic killer whales at individual and regional levels (Matthews and Ferguson 2014). Results indicate killer whales included in our sample foraged consistently at similar trophic levels, but within food webs with distinct baseline isotopic values.

An initiative of the Orcas of the Canadian Arctic project is to train and equip Inuit field teams to collect data independent of southerner support. In August 2013, the first killer whale biopsy was collected under this initiative by an Inuit field team in Pangnirtung. In 2014, killer whale sampling kits, which included all equipment necessary to collect tissue biopsies, photographs and attach satellite transmitters to killer whales, were provided to three communities (Repulse Bay, Arctic Bay and Pond Inlet). Two communities (Repulse Bay and Pond Inlet) received training in the use of provided equipment, so that killer whales could be sampled by Northerners if they were sighted. While no killer whales were encountered by researchers or trained Inuit in 2014, emphasizing a community-based approach provides a promising means to studying highly mobile killer whales in the remote eastern Canadian Arctic.

Polar Bears

Analysis of sea ice conditions in the Canadian Arctic Archipelago revealed shifts away from multiyear ice to annual ice cover. Lengthening ice-free periods may become critical for polar bears before the end of the 21st century. Polar bear populations in the Archipelago may undergo an annual 2-5 month ice-free period, where no such conditions exist presently. Business-as-usual climate projections suggest polar bears may experience conditions that challenge persistence across the entire Archipelago by 2100.

A mechanistic model was developed that allows estimating the expected low-density growth rates under a mate-finding Allee effect for polar bears before such an effect can be observed. Mate-limitation can induce long transient dynamics, even in populations that eventually grow to carrying capacity. Applying the models to the over-harvested low-density population of Viscount Melville Sound showed that a mate-finding Allee effect is a plausible mechanism for slow recovery of this population.

The improved fit of the weighted polar bear habitat model (with kill data and prey biomass) suggests that density of use alone was insufficient to define habitat quality.

Ecosystem

By assessing the Beaufort Sea shelf ecosystem and including all species, predator-prey interaction, and multiple stressors, the cumulative impacts and their effects on the ecosystem can begin to be assessed. Based on the ecosystem model, the ecosystem structure has maintained stability over time, while biomass has increased slightly. The fitted model can be used to assess ecosystem level changes over time and potential ecosystem level indicators.

CONCLUSION

Along with findings over previous years, results from research in 2014 on foraging ecology and food webs, habitat use, distribution, reproduction, and population structure continue to indicate coupling between all aspects of marine mammal ecology and the physical environment across the Canadian Arctic. Strong seasonal and inter-annual variation in measures of diet and distribution has been related to parameters such as sea ice condition and air temperature. Although we are currently in the process of determining these relationships across several spatial and temporal scales, sex-, age-, and population-specific foraging and movement behaviours indicate climate change impacts could vary within and across populations. Results from studies of foraging ecology and stress in ringed seals and beluga whales indicate shifts in diet, niche width, and chronic stress exposure suggesting ecosystem changes are already occurring. In the context of unidirectional climate change, environmental conditions could reach or exceed species' tolerances, having negative impacts on Arctic marine mammal abundance, distribution, and population structure. For all species, the fast rate of environmental change occurring in Arctic ecosystems challenges populations to adapt quickly to shifts in habitat and food web structure.

We are collecting important information on Arctic marine mammals relevant to determining how environmental variation impacts various aspects of their ecology. This information is allowing us to determine how Arctic climate warming may impact marine mammal populations, and to provide an assessment of how to mitigate these impacts. Such measures could include protection of seasonally critical areas, identification of most vulnerable populations, and direct management efforts. Study findings can be used by Northerners who will also need to adapt to preserve cultural and economic relevance of Arctic marine mammals in their communities. Future research will focus on acquiring more data in partnership with Northern collaborators, and incorporating this information into population and ecosystem models to understand and predict impacts of Arctic climate change on marine mammal populations.

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THE CANADIAN ARCTIC SEABED: NAVIGATION AND RESOURCE MAPPING

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ABSTRACT

This project undertakes the core seabed mapping component of the ArcticNet research program. Underway 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 natural hazards 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 manner however, can only proceed in a safe and responsible manner, by managing the potential detrimental impacts to the environment. A key requirement is to be able to assess potential natural hazards that might result in harmful affects both to persons and the environment. Natural hazards such as underwater landslides, collapse of offshore structures built on gassy seabeds 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 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 golden opportunity to simultaneously map uncharted regions to provide alternate pathways. (3) Past to present evolution of sea-ice regime: Understanding past climatic history is the key to 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 Navigation and Resource 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 is on the benefits of the non-living resource extraction, at the community level, far more reliance is placed on the ability to develop marine living resources. A first step towards this is properly delineating the submerged seabed morphology and habitats in the vicinity of those communities.
- **The need for improved charting in the North**: To undertake the scale of marine shipping required to support non-living resource programs in the north, and to ensure access for the development of coastal living resources, the state of nautical charting has to be vastly improved. The ArcticNet mapping program now represents the most extensive source of modern high density bathymetric surveying in the Archipelago.

For 2015, plans are to extend map coverages in fjords of eastern Baffin Island (P. Lajeunesse, G. St-Onge, G. Massé, D. Forbes) for paleoglaciology and paleoceanography. If sea ice conditions permit it, the Amundsen could sail up to Petermann Fjord, northwestern Greenland, to map this sector marked by the calving of a very large ice island in 2010.

OBJECTIVES

For the 2011-2018 period, the scientific seabed mapping needs in the coastal Canadian Arctic are projected to be dominated by the increasingly open access to previously uncharted waters and the opportunities that provides for both living and non-living resource exploitation.

Mapping toward Non Living Resource Development: Exploitation of hydrocarbons is already scheduled for the Beaufort Sea; seabed pipeline access to the Sverdrup Basin (known reserves) is a necessary precursor to that development; exploration is proposed for known hydrocarbon provinces including Lancaster Sound, Baffin Bay and Labrador margin regions; and new initiatives in frontier programs such as the Makkovik and Saglek margins, Hudson Bay & Strait and Foxe Basin are starting.

In line with ArcticNet's Strategic Framework, the updated 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.

Mapping toward Living Resource Development: Examples of marine living resource exploitation include the Davis Strait and Cumberland Sound turbot fishery and the northern and striped shrimp fishery. For neither fishery is the seabed habitat on which these species reliant adequately known. Closer inshore, potential new fisheries such as the soft-shelled clam and Greenland cockle are being investigated yet little is known about either the coastal bathymetry or the availability of suitable seabed habitat for these species.

In parallel with the non-living resource exploitation and safety of navigation, there is thus a requirement to better understand the coastal seabed habitat on a community level. The mapping component of this work is being addressed in partnership with a coastal landscapes project, a seabed habitat/benthos project, and freshwater/marine coupling project. The shoaller draft, higher manoeuvrability, and lower cost of the GN vessel (Brucker et al., 2013) are, however, far better suited to investigating the coastal habitat and safety of navigation issues that also need to be addressed.

INTRODUCTION

This project implements underway geophysical mapping programs from the CCGS *Amundsen* and the RV *Nuliajuk* in support of a wide variety of Network Investigators, parallel ArcticNet projects and external partner objectives. There is continual networking activity between the groups that run the mapping (now Laval for *Amundsen* and UNB for *Nuliajuk*), the other 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*, and *Nuliajuk*, 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 2013 and 2014 mapping has generated the first surveyed shipping corridors into several previously completely uncharted coastal fjords (Brucker, 2013). 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 12 years of opportunistic transits and site surveys by the CCGS *Amundsen* (and, since 2012, the RV *Nuliajuk*) represents the single largest holding of high density, well navigated charting information in the Arctic Archipelago. The *Amundsen* actively uses this to safely meet her science objectives. That same data has been passed on to the Canadian Hydrographic Service to update their existing chart catalogue of the Archipelago region.

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

ACTIVITIES

In the 2014 year, the following research activities involving the training of graduate students and postdoctoral fellows were performed:

CCGS Amundsen Mapping

<u>Beaufort Sea</u>*:* Five days of *Amundsen* operations were dedicated to map seafloor morphology and to core sediments in the Beaufort Sea by our NRCan collaborators S. Blasco and N. King funded by the

BREA (Beaufort Regional Environmental Assessment) project. Sediment cores were also collected for paleoceanographic studies in the region for the ISMER-UQAR team (J.C. Monterro-Serrano, G. St-Onge, A. Rochon) funded by an NSERC-STAC grant of $150,000.

Baffin Island: *Amundsen* time was also used to map seabed morphology in and offshore fjords of Baffin Island for P. Lajeunesse (northeastern Baffin) and southeastern Baffin (D. Forbes & T. Bell) for paleoglaciology and sea level histories.

Baffin Bay: Seabed mapping was also carried out in various sector of northern Baffin Bay to strategically select core sites for paleoceanography (collaborator G. Massé).

RV Nuliajuk Mapping

Shipping Lanes Access, around Cumberland and Terra Incognita Peninsulas (NI Hughes Clarke and collaborator Kennedy) using the RV *Nuliajuk* mapping system, inter island and along coastal corridors as well as specific strategic anchorages were mapped in support of GN objectives (Brucker et al, 2013).

Drowned Sea-Level Terraces, Cumberland Peninsula (NI's Forbes and Bell) using the *Amundsen* and RV *Nuliajuk* multibeam system, drowned sea level terraces (Cowan et al., 2013) were identified and mapped around SE Baffin Island.

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 2014 season allowed mapping new sectors of Baffin Bay (including offshore Greenland), Baffin fjords, Nares Strait, Chukchi and Beaufort seas (see Figure 1). These operations were undertaken by the Laboratoire de géosciences marines (ULaval) 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 nearly 10 users and is currently being used by graduate students for the thesis.

On-line Multibeam Data Management: The UNB-based multibeam data processing and on-line distribution model continues to be developed to maintain the new data from the *Nuliajuk* (http://www.omg.unb.ca/Projects/Arctic/google/). Starting in 2015, the newly acquired data will be integrated with the OMG database from previous years. This updated database will be available in Spring 2015 on a new platform developed at ULaval by the Laboratoire de géosciences marines and the GeoStat Center.

Incorporation of *Amundsen* and *Nuliajuk* Multibeam Data into CHS Nautical Charts: The mapping data, generated by the Amundsen, and the Nuliajuk, 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 ULaval. All *Amundsen* mapping logistics, operations, processing and dissemination was managed by his laboratory involving Gabriel Joyal, Etienne Brouard (PhD student) and Jean-Guy Nistad.

Figure 1. Map showing the 2014 mapping season in the sectors of Baffin Bay (including offshore Greenland), Baffin fjords, Nares Strait, Chukchi and Beaufort seas made onboard the CCGS Amundsen.

Hughes Clarke continued to manage just the RV *Nuliajuk* work as it is separately funded.

Dealing with Data Ownership Issues

Current Distribution Model: One of the greatest benefits of the ArcticNet Seabed Mapping Projects over the past decade has been the open distribution of the growing seabed mapping database. Through an internet portal, the global scientific community has been able to browse the data for the entire Archipelago at resolutions as fine as 10 m. Our greatest scientific insights into the seabed processes have come about from open availability of the serendipitous collection of transit data.

To get source data access requires just a query to UNB (merely to log usership) upon which a password was always freely given out. The latest season of data was always online within 6 months of the vessel docking. We typically receive 10-20 requests per year from all of academic, government and commercial organizations. Many of them request (and receive) bulk downloads of the entire Archipelago dataset.

Since the *Amundsen* sailed in Greenland waters in 2014, the bathymetric data acquired in this territory have been made available to the Greenland Government to increase their database.

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.

It should be noted that for the past decade CHS have received all the Amundsen data without any restrictions. And for the current field seasons they continue to receive all that data.

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:

1. Improved understanding of the glacial history and geohazard potential of the western arctic to promote responsible non-living resource exploitation.

2. Building framework bathymetric and habitat databasesin the eastern arctic to facilitate future community marine living resource exploitation.
3. Acquiring baseline bathymetric data in uncharted waters to update the nautical charting coverage, thereby improving safety of navigation across the whole archipelago.

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

While the three 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.

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CARBON EXCHANGE DYNAMICS IN COASTAL AND MARINE ECOSYSTEMS

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ABSTRACT

This project's goal is to understand how climate change will affect the air-sea exchange of climatically relevant gases (carbon dioxide-CO_2, dimethylsulfide-DMS, and nitrous oxide-N_2O). Oceans exert considerable influence on climate through their role on the global cycling of climatic active gases. For example, the world's oceans are nature's largest sink for CO_2 and they globally account for a significant proportion of the natural emissions of the greenhouse gas nitrous oxide (N_2O), and the vast majority of dimethyl sulfide (DMS) production. DMS is the largest source of sulfate in the marine environment, and once in the atmosphere the compound can trigger the formation of aerosols that serve as cloud condensation nuclei. While greenhouse gases (CO_2 and N_2O) act to warm the atmosphere, the increased production of DMS may have a cooling effect on climate by increasing back-scattered solar radiation. Our understanding of the effect that a changing Arctic climate and sea-ice regime will have on the air-sea (and sea-ice) exchange of these trace gases is currently somewhere between partially understood and mostly unknown, and hence important feedbacks that involve sea ice and the cycles of climate-active gases are currently not represented in general circulation models. A requirement of this project is to parameterize those processes affecting the distribution of dissolved CO_2, N_2O, and DMS in surface waters of the Arctic, and their exchange with the atmosphere. Newly developed parameterizations are being implemented into coupled atmosphere-sea ice-ocean biogeochemistry models to learn how the ocean's response (physical, biogeochemical and biological) to climate change and variability will affect the atmosphere-ocean cycling of these climate active gases within the Arctic, and in turn how these regional processes may affect the global budgets of these gases.

KEY MESSAGES

- A recently recovered and compiled set of inorganic carbon data collected in the Canadian Arctic since the 1970s has revealed substantial change, with variability, in the carbonate system of the Beaufort Sea and Canada Basin. The data confirms:
  - » the role of this area as a net atmospheric carbon sink, however, high pCO_2 values in the upper halocline underscore the potential for CO_2 outgassing as sea ice retreats and upwelling increases;
  - » increasing total inorganic carbon and decreasing alkalinity are increasing pCO_2 and decreasing $CaCO_3$ saturation states, such that undersaturation with respect to aragonite now occurs regularly in both deep waters and the upper halocline;
  - » a signal in the carbon system parameters associated with climate change is difficult to resolve given inter-annual variability.
- Summertime observations of sea-surface pCO_2 within northern Baffin Bay, Nares Strait, and Lancaster Sound never exceeded atmospheric values, indicating the potential of this region to act as a sink of atmospheric CO_2. Biology appears a particularly strong determinant on pCO_{2sw} in Baffin Bay and Nares Strait.
- Sea ice researchers routinely extrapolate stoichiometric equilibrium constants for the dissociation of carbonic acid in seawater to sea ice brine, which relative to seawater is both colder and more saline. Constants are used to describe the sea ice carbon system. We have confirmed that these constants, originally derived for general oceanic conditions may not be readily extrapolated to sea-ice brine systems.
- The reliable estimation of surface 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.
- As spring Arctic sea ice matures, carbon dioxide undersaturation develops and CO_2 draw-down is prevalent, particularly during the period of melt pond formation. Abiotic processes dominated inorganic carbon in upper ice and early in season. Biotic processes controlled inorganic carbon in bottom ice and late in season.
- Melt timing of snow covered sea ice is controlled primarily by synoptic scale weather systems that deliver energy to the surface via longwave radiation and turbulent heat fluxes. A recent time series of CO_2 flux measurements over sea ice highlights a link between carbon exchange at the ice surface, and weather.
- 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.
- The Lancaster Sound and the northern portion of Baffin Bay represents a strong source of dimethylsulfide (DMS) in July, with concentrations regularly above 6 nmol L^{-1}. Preliminary analysis of the NETCARE data indicates that these high DMS concentrations and fluxes are associated with new particle formation in the lower atmosphere.
- Melt ponds can represent a source of DMS for the atmosphere as important as the open water in the Arctic. Organisms and processes responsible for melt pond DMS are still under investigation.

OBJECTIVES

This project's goal is to understand how climate change will affect the air-sea exchange of climatically relevant gases (carbon dioxide-CO_2, dimethylsulfide-DMS, and nitrous oxide-N_2O). To achieve this goal the team needs to learn how pertinent seawater biogeochemical properties in the Canadian coastal Arctic environment will respond to change.

Working objectives in support of this mission include:

- To determine the main sources of variability in the carbonate system of seawater across the ArcticNet domain and to understand how these drivers change seasonally;
- To determine the main sources of variability in the sea ice carbonate system for the variety of ice types observed across the ArcticNet domain and to understand how air-ice, and ice-to-ocean carbon transport responds to this variability;
- Exploit knowledge associated with preceding objectives to develop explicit relationships for air-sea and air-sea ice CO_2 exchange;
- Development of robust parameterizations for surface CO_2 exchange in Arctic seas with and without sea ice;
- Assess the importance of ice margins, melt ponds and surface microlayer as sources of DMS and new production of aerosols in the Arctic;
- Development of robust biogeochemical ice-ocean models optimized for seawater carbon, nitrogen and sulfur systems;
- Explore the sensitivity of acidification and carbon and trace gas exchange to weather/climate and ocean properties using robust biogeochemical ice-ocean models; and
- Quantify carbon and trace gas budgets in Arctic seas at a variety of scales through the inclusion of robust biogeochemical ice-ocean models into global and regional climate/ocean models.

INTRODUCTION

The "ocean carbon sink" presently offsets ~30% of anthropogenic emissions, and has helped restrain the accumulation of CO_2 in our atmosphere (Ciais et al., 2013). However, not every ocean region acts as a strong CO_2 sink, and the carbon exchange behavior of many oceans is presently being modified by climate change. This is particularly true in the Arctic Ocean where observations have documented pronounced change, including: significant warming (Steele et al., 2008), a thinner younger sea-ice cover that is absent altogether for a longer portion of the annual cycle (Nghiem et al., 2007), invigorated cyclone activity (Simmonds and Keay, 2009), and a freshening surface waters (Manabe et al., 2004; Lenaerts et al., 2013). Best, albeit dated, estimates for the CO_2 budget in the Arctic Ocean show a stronger than average sink, but sea-ice loss, surface warming, freshening, and a changing ecosystem are all likely to impact carbon uptake (Bates & Mathis, 2009; McGuire et al., 2009). Overall, the predicted trend is towards more CO_2 absorption by the Arctic Ocean, but significant variability through space and time is anticipated. Ongoing changes in the Arctic Ocean are also likely to permit an increased exchange of other climate-active gases, such as dimethylsulfide (DMS). DMS, a biogenic gas linked to cloud formation, is expected to be produced in increasing amounts as the sea ice cover recedes (Levasseur, 2013).

A result of diminishing sea-ice concentration and extent in the Arctic is the increased potential for air-sea gas exchange, particularly over the extensive Arctic shelves which are ice-free over larger temporal and spatial scales. A retreating and thinning sea ice cover should enhance the ocean's uptake of CO_2 (Bates and Mathis, 2009), and possibly the air-sea fluxes of other biogenically-produced climate-active gases, including DMS. Given the complexity of the system, a number of competing outcomes to change may impact the strength of the Arctic CO_2 sink: 1) CO_2 draw-down potential will be limited because of water column stratification associated with a freshening of the Arctic

Ocean. In this scenario uptake will be dampened because of nutrient limitation on primary production, and in absence of mixing the surface layer will warm raising the partial pressure of CO_2 (pCO_2) (Cai et al., 2010; Else et al. 2013). 2) The prevalence of open water and mobile sea ice may encourage episodes of the vertical mixing. While strong upwelling will replenish nutrients in the surface layer, thereby supporting primary production (e.g., Tremblay et al., 2011), the concomitant introduction of inorganic carbon from the halocline will tend to supersaturate CO_2 in the surface layer relative to atmospheric levels, transforming a region which may otherwise exist as CO_2 sink into a source of atmospheric CO_2 (Else et al., 2012a,b, Lansard et al., 2012; Mucci et al., 2010). 3) The question of increasing river discharge into the Arctic (Peterson et al., 2002) is important given microbial and photochemical mineralization of organic carbon to CO_2 in the upper mixed layer is typically efficient in ocean margins (Fichot et al., 2014; Guéguen et al., 2011). The input of terrestrial carbon to Arctic has the potential reduce the efficiency of atmospheric CO_2 absorption over a vast area (Else et al., 2008b; McGuire et al., 2010). This effect may become even more intense in the future if changes to the permafrost and peatland ecosystems of surrounding watersheds result in increased (Keller et al., 2014) or altered (e.g., Woods et al., 2011) carbon transfers to the marine system. 4) A consequence of the 'new' ice regime is greater ice production during the cold season, which may enhance a sea ice carbon pump (Rysgaard et al., 2009; 2011), ultimately pushing the system toward stronger CO_2 uptake (Else et al. 2011).

Dimethylsulfide (DMS) is the most important source of material for secondary aerosol formation (and cloud condensation nuclei) in the marine boundary layer (Lovelock et al. 1972). The enhanced production and emission of DMS from a warmer ocean forms the basis for a negative feedback through an increase in backscattered solar radiation that is hypothesized to accompany the heightened loading of sulphate aerosols (Charlson et al. 1987). While a proposed climate regulation mechanism involving a feedback loop between climate warming and DMS production has been questioned (Quinn and Bates 2011), feedbacks between oceanic DMS emissions and regional climate do appear to be significant, especially in the Arctic, where warming is amplified. Peaks in DMS emissions and nucleation events were recorded during the ArcticNet/Arctic SOLAS program in Lancaster Sound (Chang et al., 2011, Motard-Côté et al., 2011). Seasonal sea ice itself is seen as a biogeochemical medium favorable to the production of DMS/P/O (Carnat et al. 2014a,b; Galindo et al. 2014), and significant DMS fluxes from sea ice have been detected in the Antarctic (Zemmelink et al., 2006; Nomura et al., 2012).

Untangling likely responses to climate change of the system's carbonate system, and emission characteristics of climate-active gases forms the basis of this project's underlying goal.

ACTIVITIES

Ship Program: CCGS *Amundsen*

In total 14 team members took part in the 2014 science cruise of the CCGS *Amundsen*. Eight participants were core to our team and an additional six contributed to the science through NETCARE collaboration. Participants were from UM, ULaval, Dalhousie, UToronto and Environment Canada. The project objectives were to examine (i) hydrographic and biological drivers of the carbonate system variability, by determining the involved water masses and the biological modulation of the hydrographic signal, (ii) the effects of said drivers on air-sea CO_2 exchange, (iii) document how fresh water (ice melt and river water) influence surface water pCO_2 and air-sea CO_2 exchange, (iv) the dynamics, distribution and production of DMS and aerosols in ice edge and melt ponds, and within the surface microlayer, (v) to quantify the prevalence and composition of a surface micro-layer. Complementary NETCARE objectives were to understand aerosol and trace gas (beyond CO_2)

production from Arctic waters and their implication on climate. Our geographic focus was the North West Passage of the Canadian Arctic Archipelago (CAA), Southern Beaufort Sea, Canada Basin, Baffin Bay and Nares Strait. The Baffin Bay data from the 2014 expedition will be compared to data gathered during the 2013 and 2007/2008 CFL/ARCTINET expeditions, and the earlier 1998 North water Polyna study in order to gain first insights in temporal variability of the Baffin Bay system. Monitoring and on-site experiments consisted of basic ship- and boat- (zodiac and barge) based sampling of water for flux, microclimate (meteorological and radiation elements), carbonate chemistry, pCO_2 and oxygen-18. The dissolved CO_2 concentration in water was measured using an automated flow through air-water CO_2 monitoring system.

This cruise of the CCGS *Amundsen* was pivotal to the NETCARE sub-project *Ocean-Atmosphere Interactions*. Coordinated sampling with the Polar6 plane was successfully accomplished on three separate occasions allowing, among other objectives, for the sampling of the ship's emissions plume. A microlayer sampling program was developed around the ship's zodiac.

Ice Camp: Daneborg Research Station - East Greenland

Five team members (N. Geilfus, T. Papakyriakou, S. Rysgaard, L.-L. Sørenson and S. Wickström) participated in the 2014 sea ice system experiment that operated between April and July from the Daneborg research facility in eastern Greenland. Team focus was air-ice-ocean CO_2 exchange in a fast-ice system typically overlain by a thick snow cover. The site conditions provided a contrast to ice and surface conditions usually observed in the CAA and as such provided the opportunity to examine the influence of deep snow on the sea ice carbonate system. A multidisciplinary dataset was collected providing insight into physical and biological drivers of carbon transport across the ocean-ice-air interface. Coincident measurements were made in the CAA as part of the springtime Arctic-ICE experiment near to Cambridge Bay, NU in the CAA (below) providing the contrast to this experiment's result. In Greenland our project benefited from considerable logistical and financial support through the CEOS-CERC program and the Arctic Science Partnership. Data are currently being processed by MSc student Wickström.

Ice Camp: Cambridge Bay, NU

Three team members participated in the Arctic-ICE springtime sea ice study near to Cambridge Bay, NU during the months of May and June. The fast ice regime in the region characteristically has a shallow snow cover, yet thicker ice development relative to the Greenland fjord system near to the Daneborg research station. The ice camp provides a unique opportunity for multidisciplinary study into sea ice and upper ocean biology, biogeochemistry and geophysics over the spring to summer transition in this environment. This year's focus was air-ice CO_2 exchange and ice-ocean carbon transport processes in a fast-ice system typically overlain by a thin snow cover. Data are currently being processed by MSc students Wickström and Diaz.

Modelling

In addition to field activities, we analyzed data from previous ship- and ice-camp experiments, and government databases and forwarded data and process-relevant information to modellers.

Work has continued with the Global Ocean Turbulence Model (GOTM) (now including sea ice) with the aim of implementing an additional biological component representing ice algae. The pelagic ecosystem has been adopted to the Arctic. Graduate students are currently implementing the dissolved inorganic carbon cycle (and alkalinity) in the water column. The DMS cycle within sea ice has been coupled to the ice algae model. Revisions to the model include an improved parameterization for radiative transfer through snow and sea ice. The resulting 1D model is forced by atmospheric and water column variables supplied by our group representative of conditions surrounding Resolute Bay. The purpose is to establish appropriate parameter fitting for landfast sea ice in the Canadian Arctic Archipelago. Similar comparisons will be made in the South Beaufort Sea and other Arctic locations in support of CCCma 3D Arctic regional model. In parallel, we have been compiling an assessment on trends and projections affecting the marine ecosystem in the Canadian Arctic including the evaluation of global and regional models.

RESULTS

Sea-Ice Carbon Chemistry and Sea Ice - Ocean Carbon Transport

K.A. Brown, L.A. Miller, M. Davelaar, R. Francois, and P.D. Tortell, 2014. Mar. Chem. 165: 36-45, doi: 10.1016/j.marchem.2014.07.005. Over-determination of the carbonate system in natural sea-ice brine and assessment of carbonic acid dissociation constants under low temperature, high salinity conditions.

High salinity brine contained within the sea ice is of particular importance in the polar carbon cycle as inorganic carbon is seasonally stored within the brine, and the brine (with inorganic carbon) is exported into and beyond the mixed layer–potentially contributing to the sequestration of carbon. Understanding the role of sea ice in the polar carbon cycle depends on the accurate characterization of the inorganic carbon system within the ice. There is considerable confidence in our ability to predict the distribution of inorganic carbon in seawater given some basic measurements, however these have not been validated for the high salinity and low temperature environment of sea ice brine. Brown et al., (2014) assessed the validity of carbonic acid dissociation constant parameterizations used for seawater for application to low temperature and high salinity brine against measured values and noted deviations between 10% and 150%, and highlighted the need for rigorous laboratory-based investigations.

K.A. Brown, L.A. Miller, C.J. Mundy, T. Papakyriakou, R. Francois, M. Gosselin, G. Carnat, K. Swystun, P.D. Tortell, Accpeted. J. Geophys. Res. Oceans. Inorganic carbon system dynamics in landfast arctic sea ice during the early-melt period.

Observations based on a 6-week time series of carbon system parameters and stable isotope measurements during the spring to summer transition of sea ice in the CAA revealed significant shifts in the carbon system of sea ice and brine (Figure 1). Seasonal shifts were associated with the summertime rise in temperature and build-up of Chl-a in the bottom ice. At the ice base, biological carbon uptake maintained undersaturated pCO_2 conditions throughout the time series, while pCO_2 was saturated in the surface ice. The low permeability of the sea ice impeded CO_2 efflux to the atmosphere. The pCO_2 in the sea ice decreased below atmospheric level with the seasonal transition transitioning the system from a net source to sink.

J. Sievers, Sørensen, L.-L., Papakyriakou, T, Sejr, M.K., Søgaard, D.H., Barbrer, D., Rysgaard, S., Winter observations of CO_2 exchange between sea-ice and the atmosphere in a coastal fjord environment, Review, The Cryosphere.

The general trend in sea ice pCO_2 and flux reported by Brown et al. (review) for sea ice in the CAA is supported to some degree by the direction of fluxes (up or down) observed over sea ice associated with the 2012 Daneborg study in eastern Greenland (Sievers et al., in review). Flux measurements show that that although the sea ice can act both as a source and sink to CO_2 (ranging between -3.2 to 1.96 µmol $m^{-2}s^{-1}$) the prevalence is for uptake during the spring/summer season. Using data from the 2012 study, Sievers et al.,

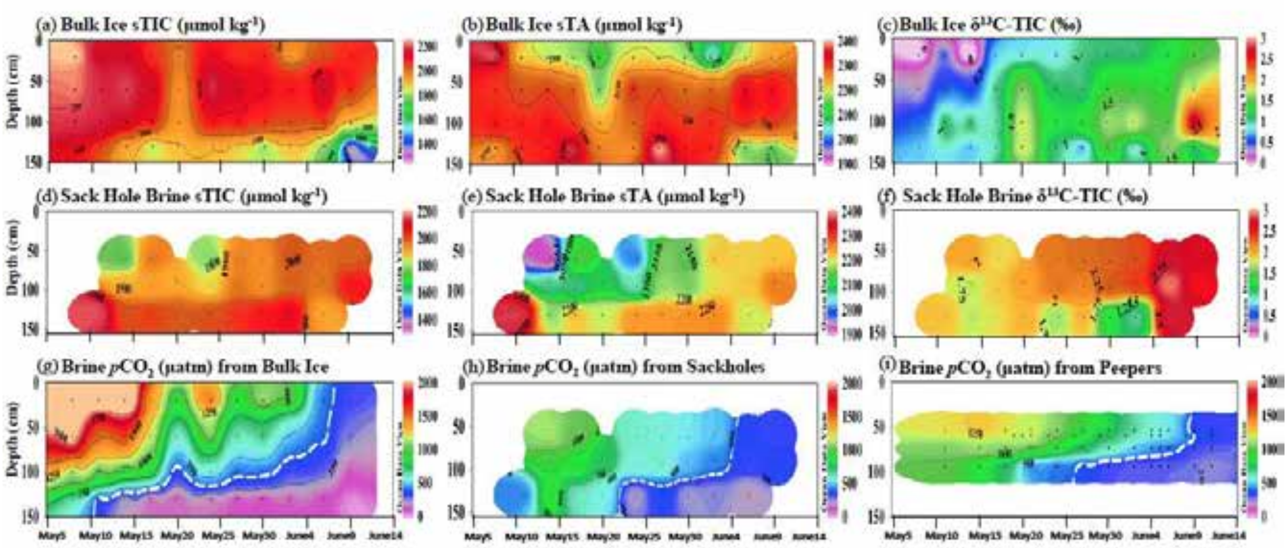

Figure 1. Six week time series of carbonate system parameters in sea ice and sackhole brine. Prefix "s" denote alkalinity (TA) and dissolved inorganic carbon (TIC) normalized to 32.5. White dashed lines in panels g-i denote saturation with respect to atmospheric pCO_2. From Brown et al., 2015. © 2015, John Wiley and Sons. © 2015. American Geophysical Union. All Rights Reserved.

(in review) demonstrates a strong association between the air-ice carbon flux and surface heating through radiation and sensible heat. The link appears through the effecting of heating on carbon chemistry of brine at the snow/ice ice interface. Associations are shown in Figure 2. Manuscript preparation is underway for the Daneborg 2014 data by MSc candidate S. Wickström.

J. Sievers, Papakyriakou, T., Larsen, S., Jammet, M.M., Rysgaard, S., Sejr, M.K., Sørensen, L.-L., Estimating local atmosphere-surface fluxes using Eddy Covariance and numerical Ogive optimization, 2015, Atmospheric Chemistry and Physics, In press.

Flux data (CO_2 and heat) over sea ice near to the Daneborg research station in 2012 has recently been used to develop a novel processing method (Ogive Optimization) for eddy covariance data (Sievers et al., 2015). Eddy covariance is a micrometeorological technique that uses high frequency (10-20 Hz) measurements of an atmospheric property (e.g., CO_2 concentration) and wind speed for a direct measure of the flux (e.g., CO_2 flux). It is the preferred approach for characterizing the gas exchange with the atmosphere for ecosystems because it is a direct measure of the flux. Because of noise, the traditional application of eddy covarinace is challenged for environments characterized by the low CO_2 fluxes, which is typical of most sea ice and some ocean environments. The approach outlined in Sievers et al. (2015) disentangles contributions to the flux by advection, and also corrects for signal loss due to sensor and site limitations. Schematically the problem is illustrated in Figure 3. Through data processing the effect of the blue shaded region (Figures 3 c, d, e and f) on flux in the figures is removed, allowing an unbiased estimate of the local flux (red shaded region in the figure).

The application of eddy covariance from a ship is further complicated through the effects of ship motion and airflow distortion. A MSc student (Zhang) has developed a methodology using signal processing to correct CO_2 flux measurements made from the CCGS *Amundsen* for both the biasing effects of ship motion

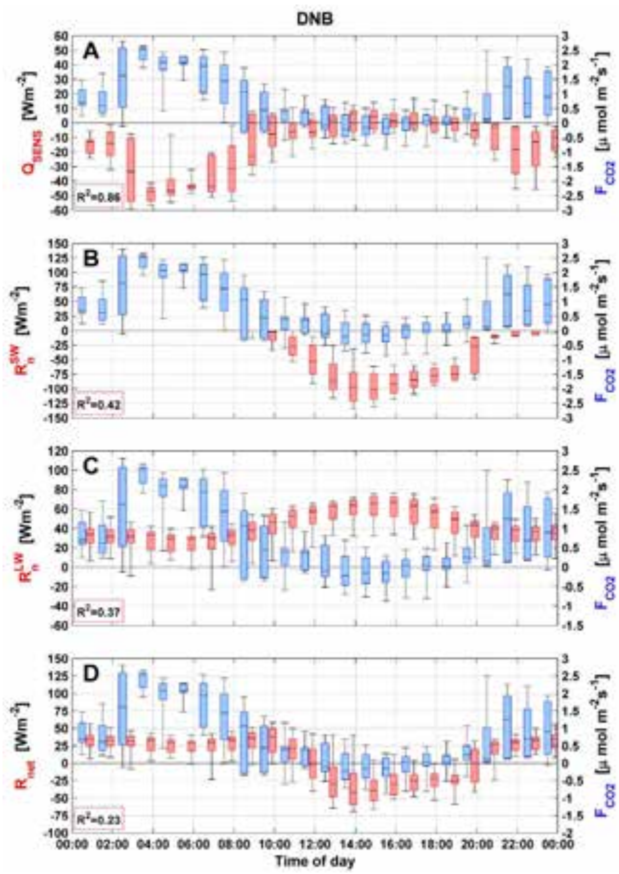

Figure 2. Diurnal patterns of (A) sensible heat flux (B) net shortwave energy (C) net longwave energy and (D) net radiative energy (red boxplots) shown alongside the diurnal pattern of CO_2-fluxes (blue boxplots) for the DNB site. Boxplots are composed of the median (black middle line), the 25-75th percentile (box) and the 9-91st percentile (black whiskers) respectively. Correlations are indicated in red boxes in the lower-left corner of each graph. Modified from Sievers et al., 2015b. © Sievers, Sørensen, Papakyriakou, Else, Sejr, Haubjerg Søgaard, Barber, Rysgaard 2015.

and flow distortion of wind as air accelerates over the ship's gunwales and superstructure (Zhang et al. in prep).

Ocean Carbon Dynamics

L.A. Miller, R.W. Macdonald, A. Mucci, M. Yamamoto-Kawai, K.E. Giesbrecht, F. McLaughlin, and W.J. Williams, 2014. Polar Res. 33, 20577, doi: 10.3402/polar.v33.20577. Changes in the marine carbonate system of the western Arctic: patterns in a rescued data set.

A recently recovered and compiled set of inorganic carbon data for the Canadian Arctic and extending back to the 1970s (Giesbrecht et al., 2014) has revealed substantial change, as well as variability, in the carbonate system of the Beaufort Sea and Canada Basin (Miller et al., 2014). The geographic distribution of total inorganic carbon (TIC) is shown in Figure 4, while the air-sea difference in pCO_2 appears in Figure 5. Striking in Figure 4 is how coverage has increased in the past 40 years and the degree of variability. Surface TIC generally decreased into the 21st century, mainly as the result of freshening and dilution due to sea ice melt and river run-off (Yamamoto-Kawai et al., 2009). The surface waters have been consistently undersaturated with respect to the atmosphere (Figure 5), an observation supported by a number of our studies (Mucci et al., 2010; Lansard et al., 2012; Shadwick et al., 2011; Else et al., 2012). Noticeably absent in the data record are IPY/ArcticNet data, which would bring the time series to 2014. Both maximum TIC (not shown) and pCO_2 was observed in the upper halocline at around 200 m of depth (Figure 5).

Surface pCO_2 and air-sea flux

Burgers et al., (in prep) Influences on the rate of air-sea CO_2 exchange within northern Baffin Bay and Nares Strait.

Surface seawater measurements of pCO_2 associated with the 2014 cruise are currently being examined by a MSc student (Burgers). There exist a great deal of variability in pCO_2 throughout the study region.

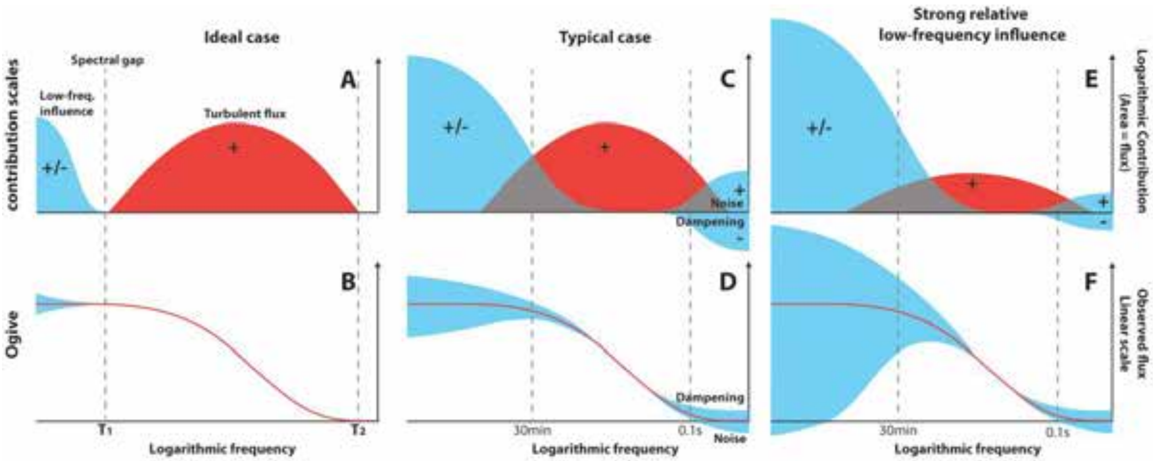

Figure 3. Top graphs show idealized co-spectra [contribution to the flux (y-axis) as a function of frequency (x-axis)]. The flux is proportional to the area under the curves (red and blue). Bottom graphs show Ogive plots corresponding to the co-spectra. Ogives are the cumulative contribution to the flux with increasing wavelength of turbulent eddy (decreasing frequency). Shown are turbulent fluxes associated with the underlying surface (red) and noise/dampening components (blue). From Sievers et al., 2015a. © Sievers, Papakyriakou, Jammet, Rysgaard, Sejr, Sørensen 2015.

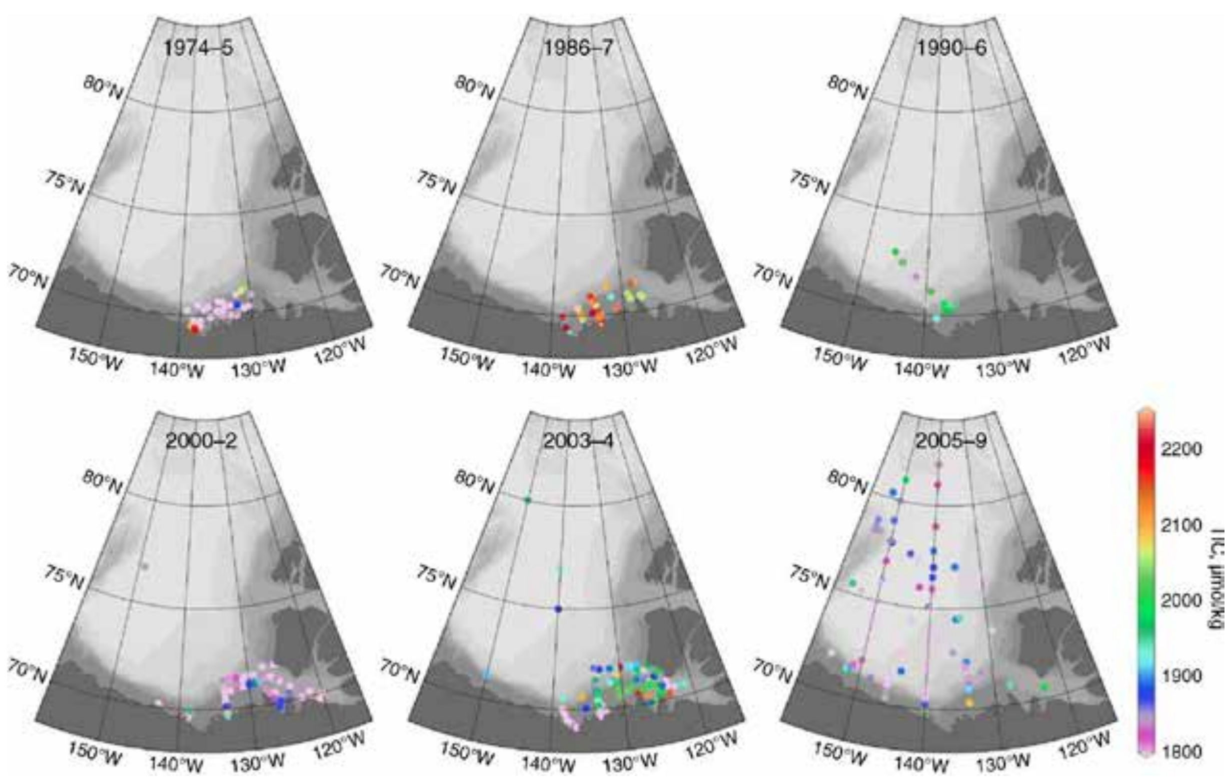

Figure 4. Maps of surface (0-20 dbar) TIC by period. From Miller et al., 2014. © Miller, Macdonald, McLaughlin, Mucci, Yamamoto-Kawai, Giesbrecht, Williams.

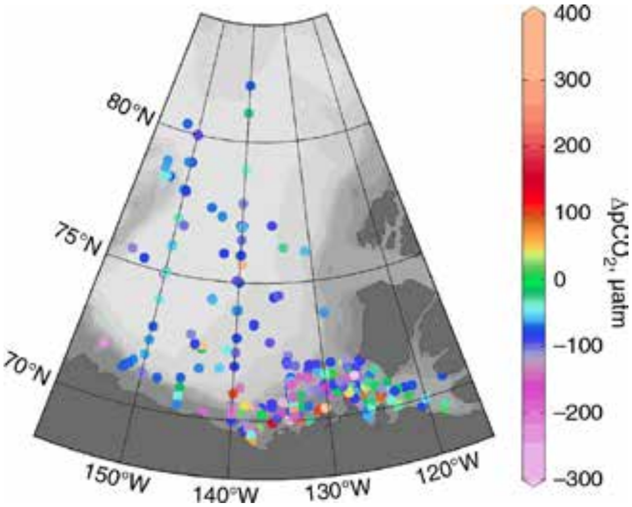

Figure 5. Air-sea pCO_2 gradient, where negative numbers indicate surface water undersaturation. From Miller et al., 2014. © Miller, Macdonald, McLaughlin, Mucci, Yamamoto-Kawai, Giesbrecht, Williams.

Nowhere in the region did the surface seawater pCO_2 exceed that of the atmosphere, indicating that the entire region has the potential to act as a significant sink of atmospheric CO_2. The variability in sea-minus-air differences in pCO_2 (ΔpCO_2; µatm) from Baffin Bay is shown in Figure 6. These air-sea differences in pCO_2 were combined with 30 minute averaged transfer velocities (k; m day^{-1}) calculated from the Sweeney et al. (2007) parameterization, in order to calculate rates of air-sea CO_2 exchange throughout the region (Figure 7). The mean uptake rate was -5.63 mmol m^{-2} day^{-1}. The maximum rate of uptake was -20.31 mmol m^{-2} day^{-1} and occurred within Barrow Strait, and the minimum rate of uptake was -0.016 mmol m^{-2} day^{-1} was observed in Kane Basin. Due to the fact that CCGS *Amundsen* would attempt to navigate away from bad weather conditions and high wind speeds, our flux estimates are most likely biased low.

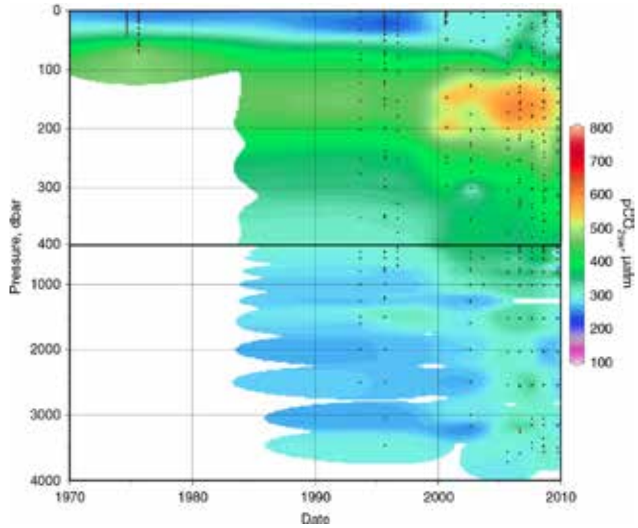

Figure 6. Vertical pCO_{2sw} distributions in the Beaufort Sea and Canada Basin. Note the emergence of high pCO_2 seawater within the upper halocline between 2000 and 2010. From Miller et al., 2014. © Miller, Macdonald, McLaughlin, Mucci, Yamamoto-Kawai, Giesbrecht, Williams.

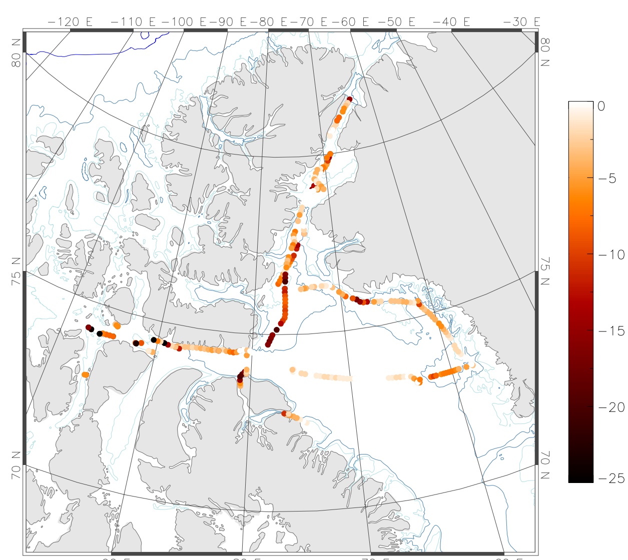

Figure 7. Estimated rates of CO_2 exchange calculated using the Sweeney et al. (2007) parameterization. Negative values denote uptake by the sea surface. From Burgers et al., 2015. © Burgers 2015.

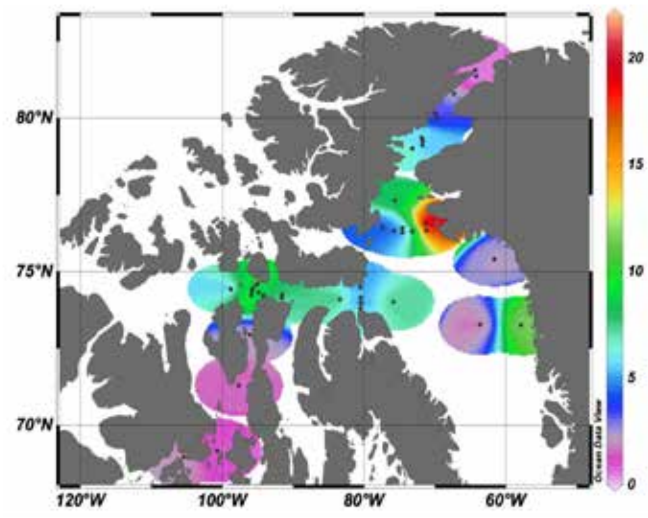

Figure 8. Interpolated surface distribution of oceanic DMS (nmol L^{-1}) during Leg 1 of the joint ArcticNet/Netcare cruise in July-August 2014 (Lizotte et al., in prep.).

Sea Ice DMS Production

Preliminary Results (2014)

A total of 10 melt ponds and 33 ArcticNet water column stations were sampled successfully during Leg 1a and 1b, along with eight impromptu stations around the Ice Island Kane II. Melt ponds samples were mainly collected in Lancaster Sound whereas the water column samples were taken at 8 light depths (100%, 50%, 30%, 15%, 5%, 1%, 0.2%, ca. 80 m) in Lancaster Sound, Nares Strait and Baffin Bay. Overall, levels of oceanic DMS were found to be high (3-10x higher than the oceanic average (3 nmol L^{-1}) in many stations of Lancaster Sound and the northern section of Baffin Bay, particularly in the upper waters of the mixed layer (Figure 8) with a characteristic tailing off at depth (Figure 9). These same regions were characterized by high concentrations of atmospheric DMS as well as the occurrence of nucleating events. DMS levels within melt ponds were found to be variable, ranging from 0-6 nmol L^{-1}.

Results from a suite of incubation experiments conducted with melt pond water from this study will

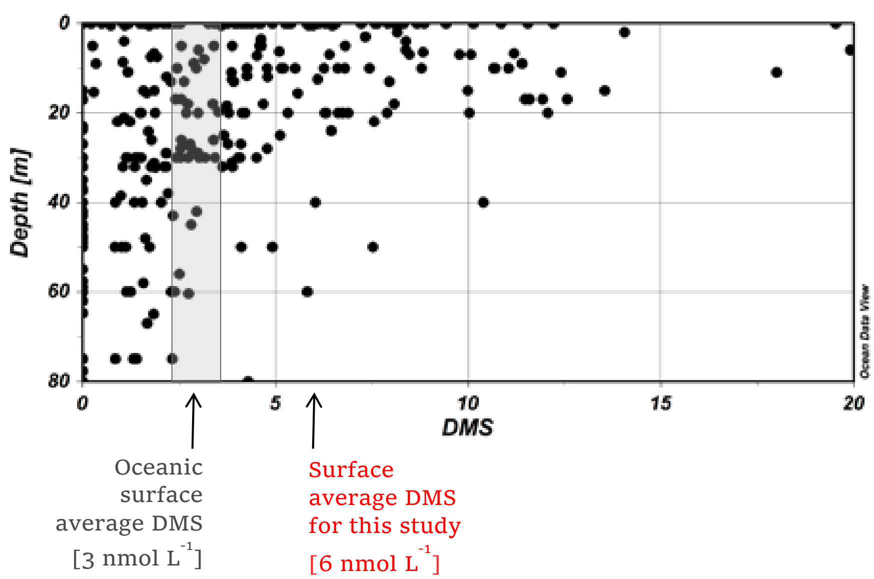

Figure 9. Scatter plot of oceanic DMS (nmol L^{-1}) from surface to 80 m depth during Leg 1 of the joint ArcticNet/Netcare cruise in July-August 2014 (Lizotte et al, in prep.).

improve our understanding of the cycling of sources and sinks of DMS in these dynamic environments that can cover up to 80% of the arctic ice sheet during spring and summer and which are in direct contact with the atmosphere. Over 2000 collected samples of DMSP and DMSO will be analyzed at U. Laval laboratories during Fall 2014 and Winter 2015.

During Leg 1b of the joint NETCARE/ArcticNet cruise in early August, we had the opportunity to follow a water mass exiting the ice pack from Kennedy Channel (81°N), down to northern Baffin Bay (77°N). Opportunities for this type of sampling are scarce but crucial to undertake within a context of climate change where predicted receding of the ice pack may result in changes in ice-edge phytoplankton dynamics and in the potential production of climate-relevant gases. Our preliminary results show an increase in oceanic DMS pools with the southward progression of the water mass (Figure 8), a deepening of the maximum DMS as the water mass ages, as well as a strong association of DMS levels with concentrations of chlorophyll a (chl-a), a proxy for phytoplankton biomass (not shown). These results suggest that changes in ice dynamics, such as the observed decrease in ice coverage within this region during summer 2014, may lead to the development of water column blooms and to the related production of oceanic DMS.

Preliminary results show no enrichment of DMS levels in microlayer waters as compared to underlying bulk waters. Samples for DMSP and DMSO will be analyzed in our U. Laval laboratory in Fall 2014 and Winter 2015.

Modeling

Two model experiments were conducted to assess the contribution of ice algal community to sea-to-air DMS flux (Figure 10 upper), as well as to the pelagic plankton community (Figure 10 bottom) using the 1-D coupled sea ice-pelagic physical-biogeochemical model simulations for Resolute Passage. Preliminary results indicate that neglecting ice algae has significant impact on the marine sulfer cycle.

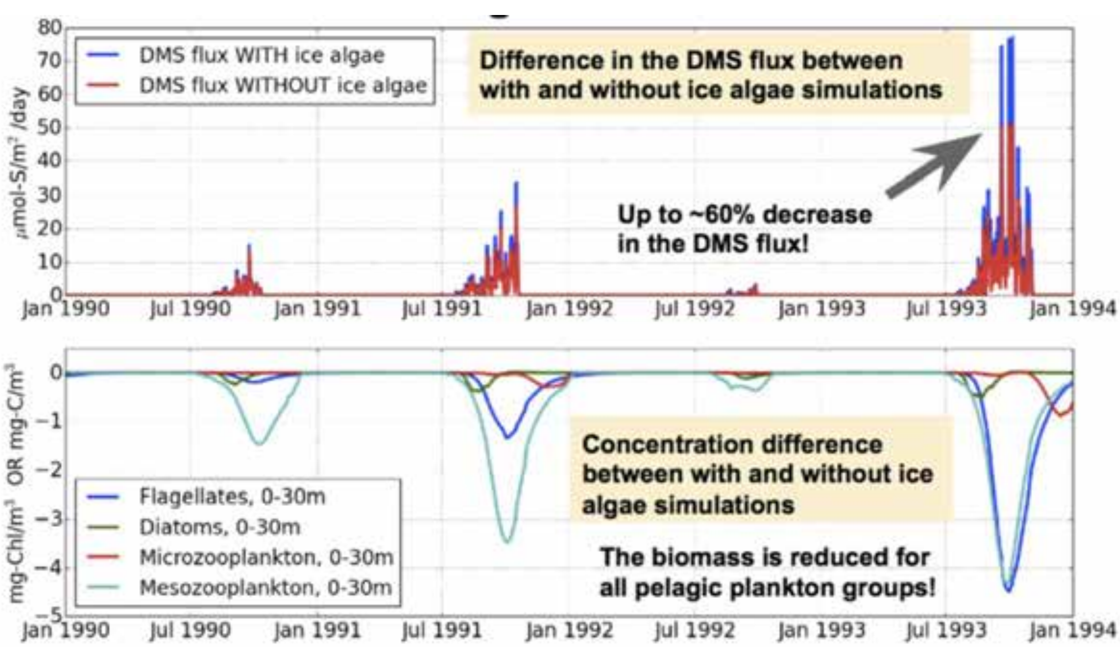

Figure 10. Simulation of DMS transport to the atmosphere (top) and under-ice concentration using GOTEM. From Hayashida et al. 2014 (available at http://web.uvic.ca/~hakase/docs/rimouski.pdf).

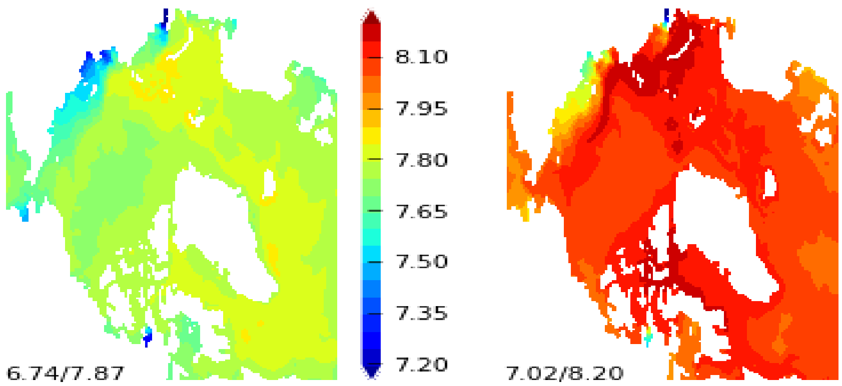

Figure 11. Surface pH for current (2006-2025) and future (2066-2085) time periods as simulated with the Canadian Arctic Ocean Ecosystem Model. Based on data from Steiner et al. 2014.

A regional ocean-ice-ecosystem model has been set up for the Arctic. The physical model and configuration is NEMO-LIM2 (Hu & Myers 2014) and the model is currently set up with the ecosystem model PISCES which is standard for NEMO. The model is also set up to run with CMOC, the simple ecosystem model which has been developed within the Canadian Earth System Model version 2 (CanESM2). The new ecosystem model to be adopted for the Arctic model and next generation CanESM is currently tested at CCCma. The forcing for recent past and future projection runs are merged data sets derived from Canadian Regional Climate Model (CanRCM4) and CanESM2 output. Initial test runs have been performed for climatological forcing averaged over 2006-2025 representing current times and 2066-2085 representing the future. Preliminary results show similarly strong reduction in surface pH as projected with the global Earth System Models (Steiner et al. 2014), but with much better resolution in the Canadian Arctic (Figure 11).

DISCUSSION

Activities this past year directly forward our objectives and are discussed under the subcategories: sea-ice carbon chemistry and ocean carbon chemistry.

Team members are international leaders in the innovation and refinement of field and analysis methods for the measurement of surface fluxes and those properties of the near surface in the sea ice and ocean that underpin air-surface exchange.

Sea-Ice Carbon Chemistry

Brown et al. (2014) highlight the potential for considerable bias in our estimation of of carbon system parameters TIC, TA, pH and pCO_2 in sea ice brines when using coefficients established for seawater. The potential for this problem has been overlooked by the research community over the past decade. In the Brown et al. study, the spread between the results from using different constants increased as a function of brine salinity, further underscoring the need for a set of carbonic acid dissociation constants relevant to sea sea-ice brine conditions. Part of the discrepancy between the constants, and the increase in this discrepancy with salinity, could result from the different ionic composition of media used to determine K_1* and K_2*. Measurements of K_2* in artificial seawater give lower values than those in natural seawater, likely due to the interactions of boric acid with HCO_3^- and CO_3^{2-}. Differences will need to be more closely considered as analytical capabilities improve.

The work of Sievers et al. (2014) arguably represents the first robust micrometeorological flux measurements of CO_2 using eddy covariance in the literature, and as such provides a mechanism to post process other of our flux data sets. The work will forward our understanding on the role of changing sea ice cover on the upper limb of the polar marine carbon cycle. This work will improve the accuracy of regional CO_2 budgets and supports our modeling initiatives.

Observations by Brown et al., (submitted) 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. 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. Although brine pCO_2 was primarily controlled by freshwater dilution, $CaCO_3$ dissolution appeared to have measurably reduced pCO_2 in the middle ice column as warming advanced. In the upper ice, gas fluxes measured in the early season confirm that sea ice can act as a source of CO_2 to the atmosphere when brine pCO_2 is above atmospheric saturation. However, CO_2 diffusion appeared to be effectively impeded, enabling the persistence of a strong gradient favouring efflux, even as warming advanced. These 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 3-10 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.

Using data from this study (average sea ice, 10-110 cm: TA/TIC = 1.08, S = 5, thickness = 140 cm; average seawater: TA/TIC = 1.04, S = 32.5, 50 m mixed layer), we estimate a relatively small net air-sea CO_2 flux for the Arctic Ocean of -0.7 Tg C yr^{-1} upon melting 8480 km^3 of Arctic sea ice. Our 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. Furthermore, our results indicate that drainage of low TA:TIC brines, 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.

Observations during this field study reveal a surprisingly dynamic carbon system within the sea ice, even before the snow had melted from the ice surface. Spatial segregation of abiotic and biotic processes during the early melt period create a heterogeneous, transitional environment in which the lower portion of the ice column can become sufficiently permeable and illuminated to support rapidly growing autotrophic communities, 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 the early melt period and drive the ice column towards pCO_2 under-saturation, contributing to a weak CO_2 sink as melt advances.

Ocean Carbonate System

Any trends in surface pCO_2 from Miller et al. (2014) are overshadowed by inter-annual variability and the seasonal distributions of the 40 year data archive. The data set is too short and seasonally biased to identify a climate-change signal in the surface waters. The data from IPY-CFL, and post CFL ArcticNet, missing from this data set and associated analysis, will be considered in subsequent analyses to extend the times series.

Perhaps more informative, from a climate-change perspective, are the variations in the subsurface waters. Although a pCO_2 maximum occurs in the upper halocline, at the same depths as the TIC maximum, the two parameters are at least somewhat decoupled. Alkalinity variations in this area are also important in setting pCO_2, and alkalinity appears to have been generally decreasing in the halocline since at least 1994. Possible explanations for the observed variations in the halocline include water-mass changes and variations in rates of transport and remineralization of shelf-derived organic carbon or of sea ice formation and brine rejection.

A deconstruction analysis provides additional insight into the causes of the pCO_2 variations in the halocline. The observed changes in temperature and salinity played a negligible role in the pCO_2 increase, while both increasing TIC and decreasing alkalinity were important. Although the overall changes between the early 1990s and the 2005-09 period indicate that decreasing alkalinity was the dominant factor in increasing pCO_2, dividing that time period into smaller intervals shows that increasing TIC concentrations were more important between the early 1990s and the 2000-04 period, and it was only during the first decade of the 2000s that decreasing alkalinity dominated the pCO_2 increase.

Whereas the role of this area as a net atmospheric carbon sink has been confirmed, high pCO_2 values in the upper halocline underscore the potential for CO_2 outgassing as sea ice retreats and upwelling increases. In addition, increasing total inorganic carbon and decreasing alkalinity are increasing pCO_2 and decreasing $CaCO_3$ saturation states, such that undersaturation with respect to aragonite now occurs regularly in both deep waters and the upper halocline (Figure 12).

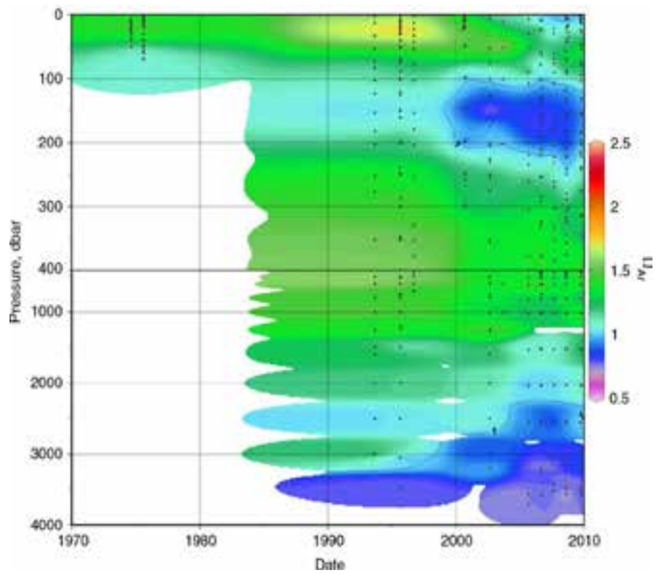

Figure 12. Vertical distributions of aragonite saturation state (ΩAr) in the Beaufort Sea and Canada Basin through time. ΩAr=1 contour shown, indicating undersaturated zones in dark blue and purple. From Miller et al., 2014. © Miller, Macdonald, McLaughlin, Mucci, Yamamoto-Kawai, Giesbrecht, Williams.

It appears Beaufort Sea/Canada Basin area is particularly inclined towards low $CaCO_3$ saturation states, because of sea-ice melt and the high- pCO2 Pacific water inflow. Therefore, even small direct anthropogenic acidification effects could tip the area into a biologically stressful state. Our time series (Figure 12) shows that the aragonite saturation state (ΩAr) is highly variable but has generally been decreasing in both the upper halocline and deep waters. Not surprisingly, the vertical ΩAr profiles mainly parallel those for pCO2, and a similar deconstruction analysis gave the same results for ΩAr. Bottom water saturation states, which are also depressed by high hydrostatic pressure, are of particular concern, because benthic communities are generally less mobile than their pelagic neighbours, and organic matter remineralization in oxic surface sediments releases additional CO2 to the bottom waters.

From the 2014 cruise (Burgers et al., in prep), more negative ΔpCO2 values were generally observed in shallower water bodies, such as Lancaster Sound and Barrow Strait, as well as shallow shelf areas along the coast of Greenland and in Kane Basin. Lancaster Sound and Barrow Strait are typically filled with landfast ice throughout the winter, with break-up beginning from the outer reaches of the archipelago in early June, and continuing towards the center of the archipelago from its periphery in July and August (Galley et al., 2012). Therefore, it is likely that the low pCO_{2sw} values observed in this region are largely due to the presence of sea ice melt in the surface seawater. Other areas exhibiting near-zero ΔpCO2 values are generally located in deeper waters, such as the center of Baffin Bay. One anomaly with very low ΔpCO2 values is located within Kennedy Channel. These measurements were quite surprising, as they were taken only one day after the break-up of an ice bridge covering this area. One hypothesis is that conditions of net-heterotrophy were present underneath the ice-cover in this region. Further investigation of the water masses impacting this area will reveal whether freshwater sources are having any impact within this area. Results are furthering our modeling initiatives.

CONCLUSION

Brown et al. (submitted) showed significant changes in sea ice and sack hole brine carbonate system parameters that were associated with increasing temperatures and the buildup of chlorophyll a in bottom ice. The warming sea-ice column could be separated into distinct geochemical zones where biotic and abiotic processes exerted different influences on inorganic carbon and pCO_2 distributions. In the

bottom ice, biological carbon uptake maintained undersaturated pCO_2 conditions throughout the time series, while pCO_2 was supersaturated in the upper ice. Low CO_2 permeability of the sea ice matrix and snow cover at the air-sea ice interface effectively impeded CO_2 efflux to the atmosphere, despite a strong pCO_2 gradient. Throughout the middle ice horizon, brine pCO_2 decreased significantly with time and was tightly controlled by sea ice temperature and in situ melt dilution. Once the influence of melt dilution was accounted for, 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 field study 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 collection of inorganic carbon data from the Canadian Arctic is increasing our understanding of the carbon fluxes in this climate-sensitive area. Both long-term time series and seasonal data underscore the fact that this area is currently undergoing dramatic changes and that the processes contributing to those changes are also in transition. Striking in the data sets are the high level of variability of surface water pCO_2, and other components of the CO_2 system.

Overall, our results from 2014 confirm the diversity of sources of DMS in the Arctic and highlighted the extremely high concentrations observed in some geographic ‘hot spots’. The presence of appreciable concentration of DMS in melt pounds heralds their possible importance as a DMS source for the Arctic atmosphere during the melt season. Factors controlling the production of DMS in melt ponds are still not understood, but may be linked to the low salinity and high light environment experienced by the microalgae trapped in this peculiar environment.

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ARCTIC GEOMICROBIOLOGY AND CLIMATE CHANGE

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ABSTRACT

The Anthropocene is a time of extraordinary change in the Arctic. The Arctic has experienced recent unprecedented variability in both the rates and magnitudes of change in the cryosphere, atmosphere, lithosphere, and dependent ecosystem function. At the same time, increased industrial development and the globalization of local economies has proceeded rapidly. These changes challenge our ability to respond and to develop coordinated and scientifically informed policies for Canada's Arctic. This project, aligned with the targeted achievements of the Canada Excellence Research Chair (CERC) in Arctic Geomicrobiology and Climate Change, will further our understanding of geomicrobial transformations as they occur in Arctic sea ice and sediments including the regeneration of nutrients required by primary producers, which are the basis of the health of all other inhabitants of the Arctic marine system. This project aims to observe, interpret and communicate key baseline information that Canadians can build upon to address key issues facing the Canadian Arctic as environmental stewards, stakeholders and governments sustainably develop its human and natural resources financially, socially and ecologically. Recent evidence suggests that microbial activity and chemical transformations within sea ice greatly influence inorganic carbonate chemistry, playing a far more important role in regulating carbon dioxide (CO_2) uptake by Arctic seas than previously anticipated. Our program aims to investigate and quantify the importance of these fundamental microbial activities using state-of-the-art assessment techniques in a comprehensive three-pronged approach of ice tank micro- and mesocosms, in situ fieldwork, and modelling studies. Combining experimental ice tank and in situ studies will provide important new insight into the regulation of these processes, their seasonal and geographical distribution, and how they are coupled between surface ocean and seafloor. In 2014-2015 physical oceanographic and sea ice physical research was undertaken, along with research into sea ice biogeochemical cycling in a sea ice tanks and during in situ studies, as well as the role of sea ice in contaminant exchange between atmosphere and ocean. Modelling activities will range from small-scale studies within sea ice and sediment compartments to local coastal regions of strategic importance and the large-scale systems of the Arctic Ocean and its peripheral seas. This project aims to produce models of coupled physical-biological processes in the Arctic marine system, increasing our predictive capacity and therefore our ability to inform future environmental conditions.

KEY MESSAGES

Physical Oceanography

- We have provided the first evidence of a strong polynya-generated impact on water properties within a high Arctic fjord in Northeast Greenland, expanding the current view of Atlantic-dominated exchanges observed elsewhere in Greenland.

Sea Ice Physical Properties and Processes

- Brine drainage channels may be established concurrent with ice growth.
- 3D MR images obtained in as little as 4 min 30 sec may be used to compute accurate vertical profiles of young sea ice liquid volume fraction.
- Frost flowers are formed by deposition of vapour provided by liquid brine skim on the surface of the sea ice.
- Frost flower degradation occurs via sublimation.
- Melt timing of snow covered sea ice is controlled primarily by synoptic scale weather systems that deliver energy to the surface via longwave radiation and turbulent heat fluxes.

Sea Ice Biogeochemical Cycling

- Ikaite precipitation and dissolution are highly dynamic in sea ice.
- Ikaite precipitates in sea ice when temperatures are below −4°C creating three distinct zones of ikaite concentrations: (a) a millimeter-to-centimeter-thin surface layer containing frost flowers and brine skim with bulk ikaite concentrations of >2000 µmol kg^{-1}, (b) an internal layer with ikaite concentration of 200–400 µmol kg^{-1}, and (c) a bottom layer with ikaite concentrations of <100 µmol kg^{-1}.
- Snowfall events may cause sea ice warming causing ikaite crystal dissolution.
- Bulk sea ice gas composition is 27.5% O_2, 71.4% N_2, and 1.09% Ar, located in air inclusions (bubbles).
- Gas transport in sea ice in winter is controlled by diffusion at rates on the same order as aqueous diffusion.
- Methane exists within sea ice, mostly inside bubbles.
- Bulk sea ice pCH_4 is markedly higher than the average atmospheric methane concentration.
- Subarctic sea ice can be a sink for atmospheric CO_2 while being a source of CH_4.
- Melting sea ice acts as a sink for atmospheric CO_2. The magnitude of this sink is increased during melt pond formation.
- Percolation of low pCO_2, low salinity melt pond water decreases the brine pCO_2 in sea ice in concert with increased ice temperatures. Melt ponds contribute additional CO_2 uptake by sea ice previously unaccounted for.
- An underwater eddy covariance system has been designed for simultaneous measurements of ocean-ice oxygen, heat, salt, and momentum fluxes.
- Testing of this system at the Sea-ice Environmental Research Facility has shown the potential for significant improvements in our understanding of ice-ocean exchange.
- A field deployment of the underwater eddy covariance system near Cambridge Bay showed interesting diurnal patterns in salt exchange, heat flux, and ice algae productivity.

Contaminants

- Sea ice may facilitate the delivery of organic contaminants to the Arctic marine food web.

- Organic contaminants may be concentrated in brine, under-ice seawater, and melt ponds.
- CUPs pose a particular risk of increased exposures via dry deposition to melt ponds, likely an important loading route of selected CUPs to the Arctic Ocean.

OBJECTIVES

The overarching objective of the Canadian Excellence Research Chair (CERC) unit in Arctic Geomicrobiology and Climate Change at the University of Manitoba is to investigate and quantify the importance of fundamental geomicrobial processes in ice-covered marine environments using state-of-the-art methodology.

Physical Oceanography

The impact of a polynya on water properties in a northeast Greenland fjord

1. Examine the fjord circulation regime and determine the impact of a polynya on water dynamics throughout the winter;
2. Analyze the impact of a polynya on sea-ice growth and the carbonate system;
3. Quantify the impact of oceanic heat on landfast sea-ice ablation, and determine the role of local dynamics on ocean-to-ice heat exchange processes.

Sea ice Physical Properties and Processes

Shape, distribution and formation timing of brine inclusions in young sea ice using Magnetic Resonance Imaging

1. Determine if brine inclusions in sea ice can be imaged in three-dimensions using MRI;
2. Determine the amount of time it takes to form a brine channel in young sea ice;
3. Determine if three-dimensional MR images of sea ice can be used to compute accurate vertical profiles of liquid volume fraction;
4. Examine synoptic weather controls on melt onset of landfast sea ice via energy balance techniques.

Micrometeorological and thermal control of frost flower growth and decay on young sea ice

1. Observe the physical and thermal properties of a thin sea ice surface prior to and during frost flower formation, growth, and degradation;
2. Quantify the sea ice, atmospheric, and radiative conditions that accompanied the life cycle of the observed frost flowers.

Shape, distribution and formation of air inclusions in young sea ice using X-ray imaging

1. Provide horizontal and vertical distribution of sea ice air-filled porosity,
2. Determine the relationship between gas-filled porosity and bulk-ice gas content.

Sea Ice Biogeochemical Cycling

Greenhouse gas dynamics associated with sea ice and snow in Young Sound

1. Document how the physical and biogeochemical properties of sea ice from winter to spring melt affect the exchanges of major greenhouse gases (CO_2, CH_4, N_2O) across the double air-sea ice-ocean interface;
2. Assess the interaction of this changing sea-ice cover with the atmosphere above it and the underlying seawater;
3. Examine the spatial and temporal distribution of melt ponds and their impact on the underly-

ing sea ice and seawater and related CO_2 fluxes with the atmosphere;

4. Determine the relative contribution of biological and abiotic processes to carbon dynamics and nitrogen dynamics during melt ponding over sea ice;
5. Elucidate the role of sea ice as a source or sink for atmospheric CH_4 and N_2O.

Air-ice fluxes and the spring/summer evolution of the surface heat budget

1. Study the interrelationships among surface fluxes of heat, radiation and CO_2 over a fast ice system and seasonal changes in both the surface ice/snow volume and atmosphere.

Underwater eddy covariance measurements of heat, salt, and dissolved oxygen

1. Study the exchange of salt, heat, and oxygen between sea ice and the underlying seawater using novel underwater eddy correlation instrumentation.

Sea Ice-Associated Biology

Assessment of algae and bacteria contributions to the production of sea ice carbon

1. Investigate the use of oxygen optodes in quantifying sea ice primary production;
2. Document changes in sea ice community productivity and algal taxonomic composition over the spring bloom and between high and low snow covers;
3. Assess the dominant environmental factors driving variability in sea ice productivity.

Contaminants

The importance of sea ice in the delivery of contaminants to the Arctic food web

1. Describe the role sea ice plays in the delivery of various OCPs and CUPs to marine food webs;
2. Model organic contaminant concentrations in melt ponds in the Beaufort Sea area based on the measured concentrations in seawater and air;
3. Describe how the ablation rate and subsequent ponding mechanisms control contaminant exchanges between melt ponds and the atmosphere;
4. Predict how changing sea-ice conditions in the Beaufort Sea, namely a shift from perennial to annual ice, may affect loading of organic contaminants to the Arctic Ocean via dry deposition to melt ponds and subsequent flushing.

INTRODUCTION

Physical Oceanography

Young Sound in northeast Greenland (Figure 1) is covered by landfast ice from late October to July each year, extending 10-30 km from the fjord mouth and eliminating wind stress on the water column. Openings in this sea-ice cover allow for intense thermodynamic sea-ice formation and brine release causing dense water formation (Rudels, 1990). Brine rejection associated with ice formation results in brine-enriched shelf waters, causing accumulation of dense shelf waters near the bottom (Anderson et al., 2004, Bauch et al., 2012), affecting the renewal and ventilation of deep water in Arctic fjords (e.g. Skogseth et al., 2013). The associated water dynamics remain poorly understood due to scarcity of in situ oceanographic observations, specifically along the East Greenland

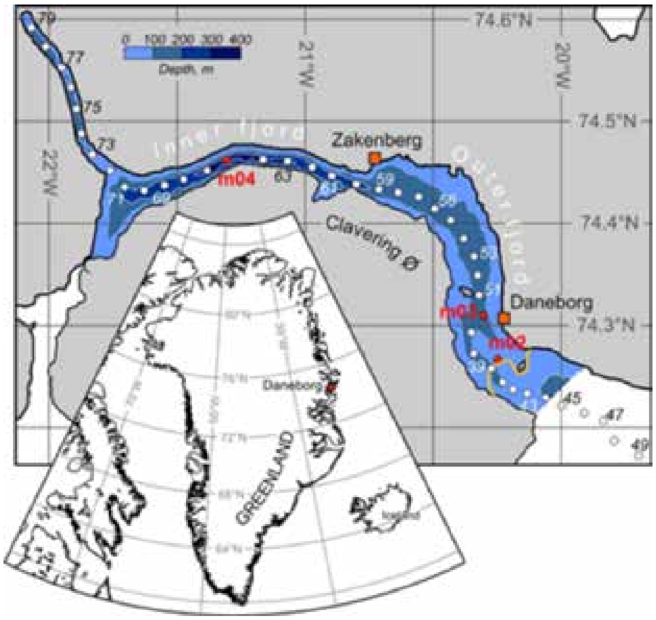

Figure 1. The Young Sound Fjord with position of CTD stations in May 2014 (white circles). Red circles indicate the ice-tethered oceanographic moorings deployed in October 2013.

Shelf and more broadly in coastal areas including the numerous deep fjords of northeast Greenland.

Ocean-to-ice heat flux is critical to the thermodynamics of sea ice, strongly affecting the exchange of heat across the air-water interface (Maykut and Untersteiner, 1971). During winter, heat flux to the ice bottom from warmer water at depth is largely unquantified, as it is controlled in part by local dynamics and thermohaline processes (Omstedt and Wettlaufer, 1992). The channel-like topography and shallow entrance sill of Young Sound (Figure 1) highly restricts water dynamics making it easier to investigate processes in the fjord interior and their influence on seasonal changes in sea ice.

Sea Ice Physical Properties and Processes

The crystal structure of sea ice and its inclusions control its mechanical strength (Assur, 1960) and its ability to exchange heat, salt and radiation (Light et al., 2003), which in turn affect the atmosphere above and the ocean below, physically, chemically (Vancoppenolle et al., 2013) and biologically (Fritsen et al., 1994, Krembs et al., 2000). The apparent optical properties of sea ice are contingent on the distribution of gas and liquid inclusions and the electromagnetic properties of sea ice are governed by the size, shape, and orientation of these inclusions. Liquid inclusions in sea ice largely determine the volumes' heat capacity and permeability (e.g. Weeks and Ackley, 1982, Golden et al., 1998, 2007), which control bulk flow in the volume and may act to flood the sea-ice surface from below or drain the sea ice to the ocean (e.g. Vancoppenolle et al., 2007). Brine drainage channels are very important; they are likely the sites of the bulk of liquid convection (i.e. gravity drainage) to the sea ice-seawater interface (Untersteiner, 1968, Lake and Lewis, 1970, Eide and Martin, 1975, Niedrauer and Martin, 1979, Weeks and Ackley, 1986, Oertling and Watts, 2004, Notz and Worster, 2008). Notz and Worster (2009) conclude that brine drainage is governed by sea ice thickness, permeability, and the established brine density gradient.

New and young sea-ice surfaces are expected to become a more prevalent feature in the Arctic (Kwok, 2007, Maslanik et al., 2007, Kwok and Cunningham, 2010, Maslanik et al., 2011). Frost flowers are relatively short-lived crystal structures formed exclusively on new and young sea ice (Perovich and Richter-Menge, 1994). They have received much attention for their potential roles in atmospheric chemistry (Rankin et al., 2002, Douglas et al., 2005, Roscoe et al., 2011, Douglas et al., 2012, Sherman et al., 2012), carbon cycling (Geilfus et al., 2013), and microbial accumulation (Bowman and Deming, 2010), and for their impact on microwave remote sensing of sea ice (Drinkwater and Crocker, 1988, Isleifson et al., 2014).

Sea Ice Energy Balance

Although detailed observations of the sea ice energy balance leading up to ice melt are rare, a general hypothesis of the important energy balance terms has emerged. In most cases, it seems that surpluses in the net radiation balance provide the necessary energy for melt (Papakyriakou, 1999, Sedlar et al., 2011, Persson et al., 2012), which is consistent with observations over high-latitude terrestrial (e.g. Ohmura, (1982)) and glacial (e.g. Bennartz et al., (2013)) snowpacks. Turbulent heat fluxes are thought to be less important in driving melt onset, however they are known to contribute significantly to the energy budget of lower-latitude snowpacks under certain atmospheric conditions (Granger and Male, 1979). Conductive heat fluxes may be an important source of energy to the surface during the winter, but become negligible during the transition to melt (Papakyriakou, 1999, Persson et al., 2012). Given the relative scarcity of these observations and the strong potential for interannual variability, it is possible that this general theory does not apply in certain situations, making it imperative to continue to monitor the surface energy balance of sea ice, in order to understand how the relative importance of these terms may evolve in a changing climate.

Sea Ice Biogeochemical Cycling

Recently, ikaite crystals have been found in sea ice. Ikaite ($CaCO_3 \cdot 6H_2O$) is only found in a metastable state, and decomposes rapidly once removed from near-freezing water. Ikaite precipitation may play an important role in air-sea CO_2 exchange in ice-covered seas, but little is known of its spatial and temporal dynamics in sea ice.

Methane (CH_4) and its oxidation product CO_2 are both greenhouse gases. While the Arctic Ocean represents an important sink for atmospheric CO_2, with current estimates of net air-sea CO_2 fluxes from -66 to -199 Tg C yr^{-1} (Bates and Mathis, 2009, Takahashi et al., 2009), the Arctic Ocean also represents a source of CH_4 with current estimates of up to 8 Tg C yr^{-1} (Parmentier et al., 2013). The roles of sea ice and melt ponds on CO_2/CH_4 dynamics during the sea ice melt season are still poorly understood (Parmentier et al., 2013). Melt ponds are a major and increasing surface feature of Arctic sea ice during spring and summer (Rösel and Kaleschke, 2012) and require attention with respect to their potential contribution to inorganic carbon and methane dynamics associated with sea ice.

While most sea ice models neglect the air volume fraction, recent studies (Zhou et al., 2013, Crabeck et al., 2014a, b) show that most sea ice-associated gas exists within bubbles; only a minor fraction is dissolved in brine. Research is necessary on how air inclusions in sea ice affect sea ice gas dynamics. In combination with traditional sea ice analytical techniques, new non-invasive imaging methodologies including CT X-ray imaging are employed to determine the air-filled porosity of sea ice.

Sea Ice-Associated Biology

The presence of ice algae in the bottom of sea ice is most notable during the spring, when light and nutrient conditions are optimal for rapid population growth. Their spring bloom increases total Arctic primary production (Legendre et al., 1992) and provides a concentrated food source for aquatic grazers at a time when the ocean is still ice-covered (Cota et al., 1989). These biological contributions to the marine ecosystem from sea ice are needed to address the requirement of sea-ice flux and ecosystem models to incorporate ice algal biomass and production values in their calculations. In particular, the contribution of sea-ice algal photosynthesis to biogeochemical processes, and thus CO_2 conditions in sea ice, is needed to quantify the influence of sea ice on global carbon levels.

Contaminants

For decades sea ice was perceived as a physical barrier to airborne delivery of organic contaminants to the Arctic Ocean; the presence of ice cover was considered a deterrent to the flux between seawater and air (Hargrave et al., 1997). Using α-HCH as a process tracer, we postulate that first-year sea ice plays a profound role in the delivery of organic contaminants to Arctic food webs, increasing the exposure of biota through 1) high contaminant concentrations in the brine fraction of the sea ice itself (Pućko et al., 2010), 2) higher concentration of contaminants in the underlying seawater during early stages of ice formation (Pućko et al., 2013), and 3) the entry of atmospherically-deposited contaminants into surface waters mediated by melt ponds (Pućko et al., 2012). Because the efficacy of the above-mentioned processes strongly depends on the ice type (first-year ice (FYI) vs. multi-year ice (MYI)), the widespread transition from MYI to FYI in the Arctic Ocean is likewise altering the flux of contaminants to the surface ocean. Specifically, MYI presents a weak brine engine (low bulk salinity) and transient, relatively fresh melt ponds that refreeze in winter. In contrast, first-year ice forms widespread melt ponds containing more brine, and the water in these ponds enters the ocean as the ice rots and disappears annually toward the end of summer.

ACTIVITIES

Physical Oceanography

Field activities were conducted from Daneborg research station (Young Sound fjord, Figure 1) in April-June 2014 resulting in a publication (Dmitrenko et al., 2015). Between October 2013 and May 2014, four landfast ice-tethered moorings equipped with ADCP and CTD systems were deployed. The mooring-based observations were complemented by four along-fjord CTD (SBE-19plus CTD equipped with a dissolved oxygen sensor SBE-43) transects in May 2014, supplemented by profiles collected during mooring deployment in October 2013 and an ice-free summer season along-fjord CTD transect from August 2013.

Sea ice Physical Properties and Processes

Two papers, one on brine channel physical properties and processes (Galley et al., 2015a) and one on frost flower properties and processes (Galley et al., 2015b), specifically with respect to the roles these to important sea ice features may play on sea ice biogeochemical cycling, were published. The sea ice and frost flower samples used in these publications were gleaned from work at the Sea ice Environmental Research Facility (SERF) on the University of Manitoba campus. The sea ice samples were imaged via magnetic resonance at the National Research Council Institute for Biodiagnostics in Winnipeg, MB. We have also published an analysis of sea-ice energy balance, collected during a past ArcticNet supported field campaign near Resolute Bay, Nunavut (Else et al., 2014a).

Sea Ice Biogeochemical Cycling

A publication has been submitted using data collected in June 2012 on landfast sea ice in Resolute Bay, Nunavut, showing how melt pond formation and percolation through sea ice decreases the pCO_2 of sea ice and brine, leading to significant uptake of atmospheric CO_2 by sea ice. We estimate an atmospheric uptake due to seasonal sea ice melt in the Arctic on the order of -10 Tg of C yr^{-1}.

In Daneborg, Greenland (Figure 1) we performed a similar field project over 9 weeks from May to July 2014 to study CO_2 and CH_4 dynamics on melting snow-covered landfast ice in Young Sound. The evolution of the carbonate system and methane was examined using measurements of total alkalinity, total dissolved inorganic carbon and methane concentrations in melted bulk sea ice, brine and melt pond samples in association with CO_2 flux measurements over sea ice and melt ponds. Percolation of melt water from melt ponds was tracked using the isotopic ratios $\delta^{18}O$ within bulk sea ice and brine.

A publication has been submitted detailing our efforts to design and test an underwater eddy covariance system (Else et al., in review). The paper shows that useful fluxes of oxygen, heat, and salt can be observed from the system in an experimental ice facility (SERF).

Sea Ice-Associated Biology

An ice-based field campaign was undertaken in Dease Strait (69.027°N; 105.328°W) approximately 15 km offshore of Cambridge Bay, Nunavut. Over 13 weeks from March to June 2014, sea ice samples were collected and analyzed for chlorophyll a, primary and bacteria productivity, nutrients, algal taxonomy, as well as particulate and organic carbon fractions. Environmental parameters such as ice temperature, salinity and light availability were also sampled. Currently two publications based on this data are in preparation.

In conjunction with the Dease Strait biology program, the underwater eddy covariance system was deployed under landfast sea ice for approximately 8 weeks. Preliminary results from this deployment were presented at the most recent ArcticNet ASM (Else et al., 2014b).

RESULTS

Physical Oceanography

A storm event on 18-25 December 2013 with strong northerly winds exported landfast sea ice from the mouth of Young Sound to the Greenland Sea on 20 December. Thereafter, the land-fast ice edge stabilized 20 km further into the fjord, or roughly 3.5 km behind the entrance sill and ~400 m from the most sea-going mooring (m02, Figure 1). Open water formation reduced the water temperature by ~0.15°C and increased salinity at 80 m by 0.12 at m02. A polynya was maintained until early March 2014 by several consecutive strong northerly wind events exceeding 15 m/s resulting in salinity gradually increased by ~0.5, and temperature decreased by ~0.16°C. In contrast to 77-80 m, the surface layer tended to be warmer by up to 0.3°C during the period between 25 December and 4 March. Mooring m04 located in the inner fjord shows similar results though the signal is much weaker given its distance from the ice edge.

The time series of temperature and salinity at moorings m02 and m03 indicates reverse water flow between the surface layer and the layer below. Velocities at all three moorings clearly show reverse water flow and enhanced velocities during polynya opening. During the open water period the velocity in the upper 80 m of the water column is characterized by a two-layer structure with an outflow in the 40 m thick surface layer and an inflow in the layer below (40-80 m). At all three moorings, the average outflow velocity over the whole 40 m thick surface layer was ~2-4 cm/s which was two times greater than the average inflow velocity of ~1-2 cm/s in the 40-80 m layer (Figure 2).

The CTD profiles from May 2014 show the winter-modified lower layer is between 40 and 140 m and provide evidence for its advective origin. CTD profiles taken at m04 in October 2013 and May 2014 show seasonal cooling and salination down to 150 m. This layer is delineated by the intermediate temperature maximum between 30 and 40 m depth indicating the actual depth of winter vertical mixing associated with sea-ice formation, implying that the origin the 40-140 m layer is associated with polynya activity rather than vertical mixing. This layer is weakly stratified, almost homogenous with temperature slightly exceeding the potential freezing temperature, and supersaturated with oxygen.

Thermodynamic ice growth modeling indicates 60% of the total oceanic heat input to ice at m04 occurred between October and December. The averaged heat fluxes varied from 9 to 25 W m^{-2} between 27 October and 10 January and dropped to less than 4 W m^{-2} until May 20 (Figure 3). The seasonal peak heat flux of

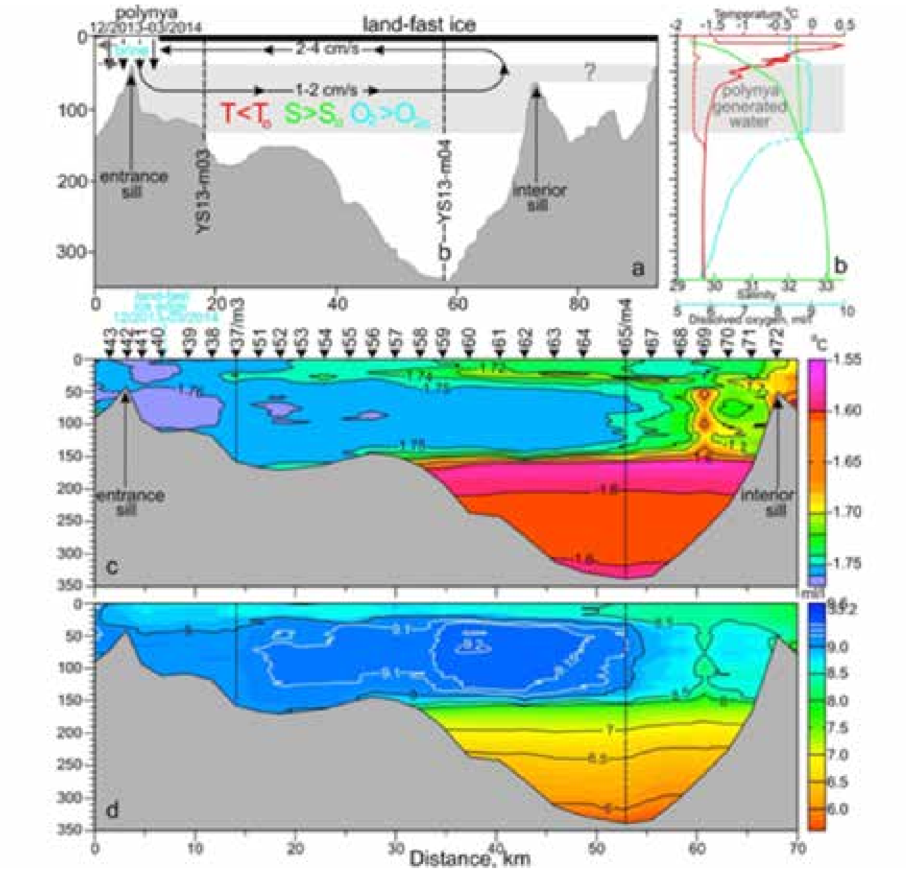

Figure 2. (a) Schematic depiction of polynya impact on circulation in Young Sound, (b) vertical distribution of temperature (red, °C), salinity (green) and DO (blue, ml/l) in 10/26/2013 (solid lines) and 5/5/2014 (dashed lines) at mooring m04, (c-d) along-fjord transect of temperature and DO. From Dmitrenko et al., 2015. © 2014 Elsevier Ltd. All rights reserved.

27-32 W m^{-2} was observed between 27 October and 5 November, before declining to 3-4 W m^{-2} between 23 November and 25 December. Two periods of amplified heat exchange occurred during winter from 26 December to 27 January and 12-23 February, with respective heat fluxes of 20-24 W m^{-2} and 18-22 W m^{-2}. Both episodes coincided with intensification of surface outflow observed during polynya openings over the mouth of Young Sound that resulted in an increase of surface layer velocities.

Oceanic heat was available in Young Sound throughout the entire winter of 2013/14, resulting in surface water temperatures above the freezing point. The highest impact of this heat on ice growth is evident from late October to February-March when differences between the water temperatures and freezing point were up to 0.7°C due to solar radiation from the preceding ice-free season. CTD measurements in August 2013 show surface temperatures exceeding 5-6°C.

Sea Ice Physical Properties and Processes

Three-dimensional images showing the morphology and location of liquid inclusions in sea ice using a high-resolution CISS gradient echo image MR sequence are shown (Figure 4). This MR sequence took only four minutes and 30 seconds. Guided by the growth history of the sea ice and evidence of a 4-5 cm granular sea ice cap of congelation ice growth, the top section of our sample core is 50 mm thick and

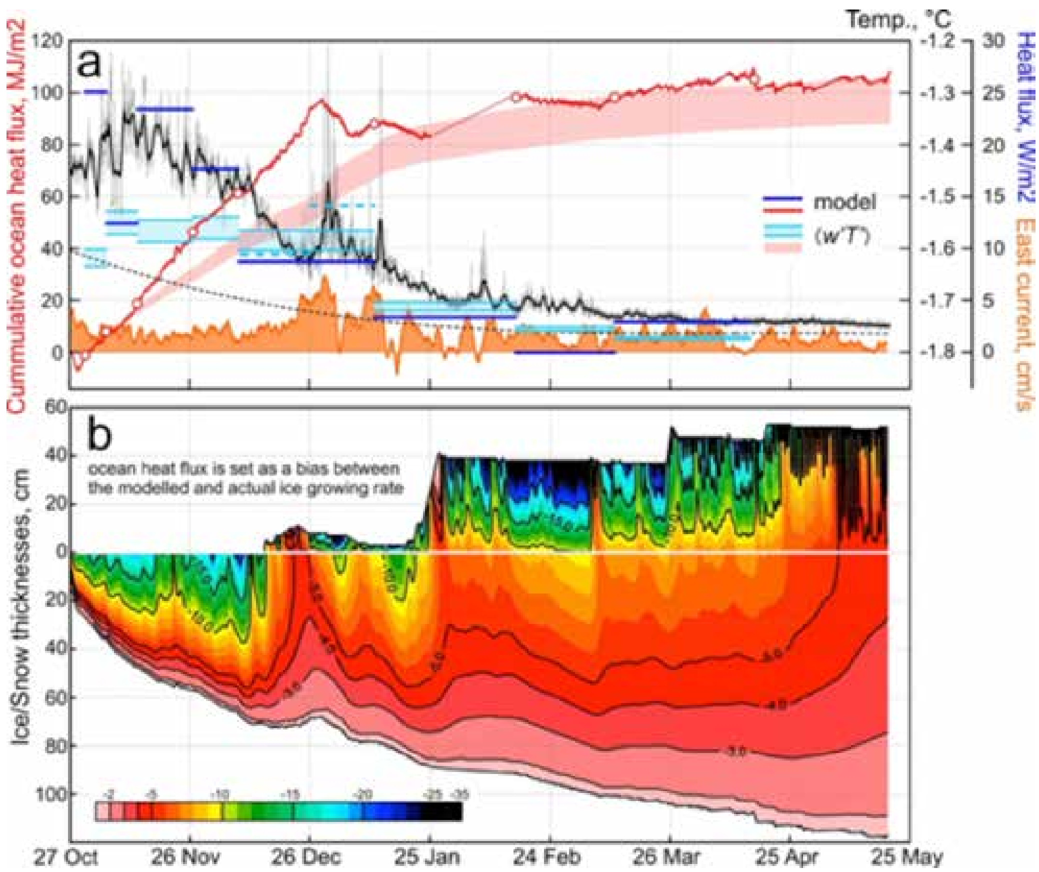

Figure 3. (a) The cumulative oceanic heat influx evaluated as a bias between the modeled and measured sea-ice thicknesses at m04. The grey and black curves specify the surface water temperature and its 24-h running mean; dashed black line is freezing point at the surface. The eastward currents from 6-m depth (cm/s) are shown in orange. (b) The temporal evolution of modeled ice/snow temperature distribution.

is comprised mainly of spherical inclusions that are randomly distributed and less than 2 mm in diameter, though a few are as large as 3 mm in diameter. The middle section of the core is about 55 mm thick, and contains very few imaged inclusions. This desalination was likely the product of warm sea-ice temperatures below the surface layer snow insulation at the surface retarding the growth rate substantially. The bottom section contained a brine drainage channel structure, 80 mm in height from the bottom of the sea ice core with its widest point (40 mm wide) 65 mm from the bottom of the core. The brine drainage channel feature imaged here in young sea ice takes the shape of a “river attended to by its tributaries” (after Lake and Lewis, 1970 who observed these features in 1.55 m thick sea ice) in the vertical, with the attending channels and elongated pockets intersecting the main vertical channel at angles less than 35° (all angles are from the vertical), though there is one channel about 30 mm in length which connects at an angle of approximately 55°.

Roughness elements are preferential sites for frost flower formation on sea ice because they are 4-6°C colder than the mean sea ice surface. A highly saline brine skim at the sea-ice surface provides the water vapour necessary for frost flower deposition on raised nodules due to supersaturation of the air immediately above the nodule as a result of the difference in vapour pressure over them compared to liquid brine skim.

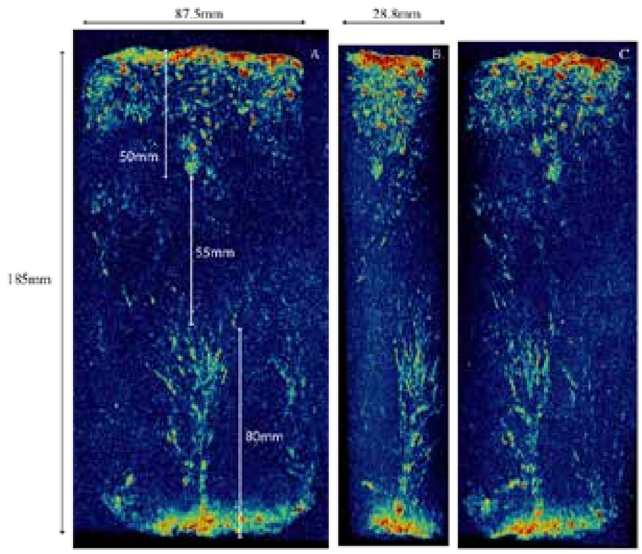

Figure 4. Magnetic resonance images in a 3-dimensional maximum intensity projection (MIP) made up of 72 images each with a thickness of 0.4 mm (Z) (28.8 mm total thickness) of a sea ice core (depth (Y) = 186 mm, diameter = 87.5 mm) viewed from the front (LEFT), side (MIDDLE) and rotated obliquely (RIGHT). These MR images can be used to compute liquid fraction profiles in sea ice (Figure 5).

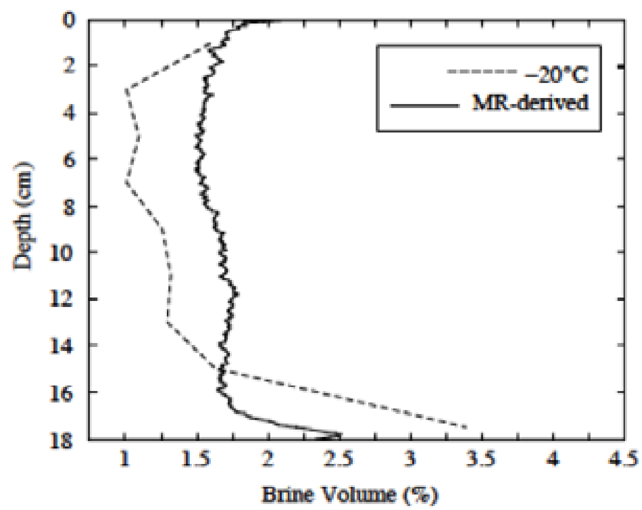

Figure 5. The brine volume (after Cox and Weeks, 1983) calculated using the observed bulk salinity data and the sample storage temperature of -20°C, to best approximate the brine volume of the sample as it was imaged by the MR scanner, and the liquid fraction at each of 290 rows (180.67 vertical mm) derived from the MR image data normalized by the highest voxel value.

Calm winds reduce or eliminate near-surface turbulent mixing, enabling supersaturation of the air above the sea ice surface (Figure 6a). The degree to which the air immediately surrounding the nodule and later the frost flower is supersaturated increases as the frost flower grows upwards, at least to the height of the supersaturated zone, suggesting that until that height frost flower growth is a self-accelerating process.

Frost flowers degrade via mass loss by sublimation at their peripheries coincident with increased air temperatures, decreased temperature differences between the frost flower and brine skim, decreased relative humidity, increased wind speeds and a shift from a negative net radiation balance at the surface to a positive one (Figure 6b).

In Else et al., (2014a), we reported the surface energy budget for landfast sea ice capturing the transition season of warming, snowmelt, and melt pond formation (Figure 7). The study was conducted in the Canadian Arctic Archipelago from 10 May-20 June, 2010. Over the first 20 days of the study we found that short periods (1-3 days) of increased net radiation (F_{net}) associated with low longwave loss (L*) provided most of the energy required to warm the snowpack from winter conditions. An extended period of low longwave loss (5 days) combined with the seasonal increase in incoming shortwave radiation then triggered snowmelt onset. Melt progressed with a rapid reduction in albedo and attendant increases in shortwave energy absorption (K*), resulting in melt pond formation 8 days later. The key role of longwave radiation in initiating melt onset supports past findings, and confirms the importance of clouds and water vapor associated with synoptic weather systems. However, we also observed a period of strong turbulent energy exchange associated with the passage of a cyclone. The cyclone event occurred shortly after melt pond formation, but it delivered enough energy to significantly hasten melt onset had it occurred earlier in the season. Changes in the frequency, duration, and

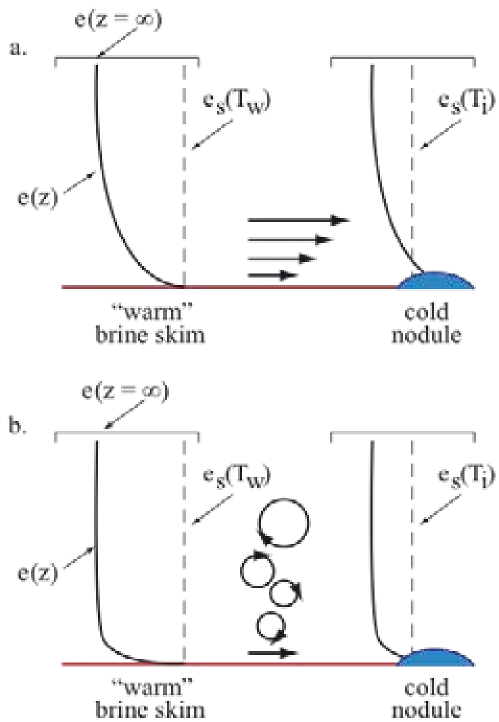

Figure 6. Schematic of growth and decay mechanisms for frost flowers. Growth is shown in panel a, where water vapour (e) supplied by the warm brine skim is at the saturation value with respect to water ($e_s(Tw)$) at the surface, and decreases with height (z) towards the far-field value ($e(z=\infty)$) following a shape typical of diffusion-controlled transport (Style and Worster, 2009). Under calm conditions, advective motion is laminar, which preserves the e(z) shape over the cold nodules. Since the saturation value with respect to ice ($e_s(Ti)$) is so much lower, local supersaturation occurs, and water vapour is deposited in the form of frost flowers. Decay is shown in panel b, where increased winds drive turbulent mixing. The mixing of unsaturated far field water vapour down towards the surface erodes the supersaturated layer over the nodules, and the frost flowers sublimate.

timing of synoptic-scale weather events that deliver clouds and/or strong turbulent heat fluxes may be important in explaining observed changes in sea ice melt onset timing.

Sea Ice Biogeochemical Cycling

We present evidence for highly dynamic ikaite precipitation and dissolution in sea ice grown at the SERF. During the experiment, ikaite precipitated in sea ice with temperatures below –3°C, creating three distinct zones of ikaite concentrations: (1) a mm to cm thin surface layer containing frost flowers and brine skim with bulk concentrations of >2,000 µmol kg^{-1}, (2) an internal layer with concentrations of 200-400 µmol kg^{-1} and (3) a bottom layer with concentrations of <100 µmol kg^{-1}. Snowfall events caused the sea ice to warm, dissolving ikaite crystals under acidic conditions. Manual removal of the snow cover allowed the sea ice to cool and caused brine salinities to increase, resulting in rapid ikaite precipitation. The modeled (FREZCHEM) ikaite concentrations were on the same order of magnitude as observations and suggest that ikaite concentration in sea ice increases with decreasing temperatures. Thus, varying snow conditions may play a key role in ikaite precipitation and dissolution in sea ice. This will have implications for CO_2 exchange with the atmosphere and ocean.

We also investigated the evolution of inorganic carbon in melting landfast first-year sea ice in Resolute Passage, Nunavut, from June 3 to June 23, 2012. Sea-ice temperature profiles became isothermal (~ -1°C) with low salinity at the surface (~0) and melt ponds started to form at the surface of the ice on 10 June. The mean total alkalinity (TA_{ice}) and dissolved inorganic carbon (TCO_{2ice}) in melted bulk sea ice of the entire ice column gradually decreased from 4 June to 21 June (Figure 8). This decrease was more pronounced in the top 20 cm of the ice cover where the minimal values were observed on 17 June. To discard the effects of concentration/dilution, we normalized TA_{ice} and TCO_{2ice} to a salinity of 5 (noted as nTA_{ice}, $nTCO_{2ice}$, respectively). The main change observed in the ice cover occurs in the top 20 cm.

From June 4 to 10, brine salinity decreased from 55 to 23 (Figure 9). Starting on June 10, low brine salinities were found at 20 cm depth while deeper brine ranged from 11 to 30, except on June 17 where low salinities

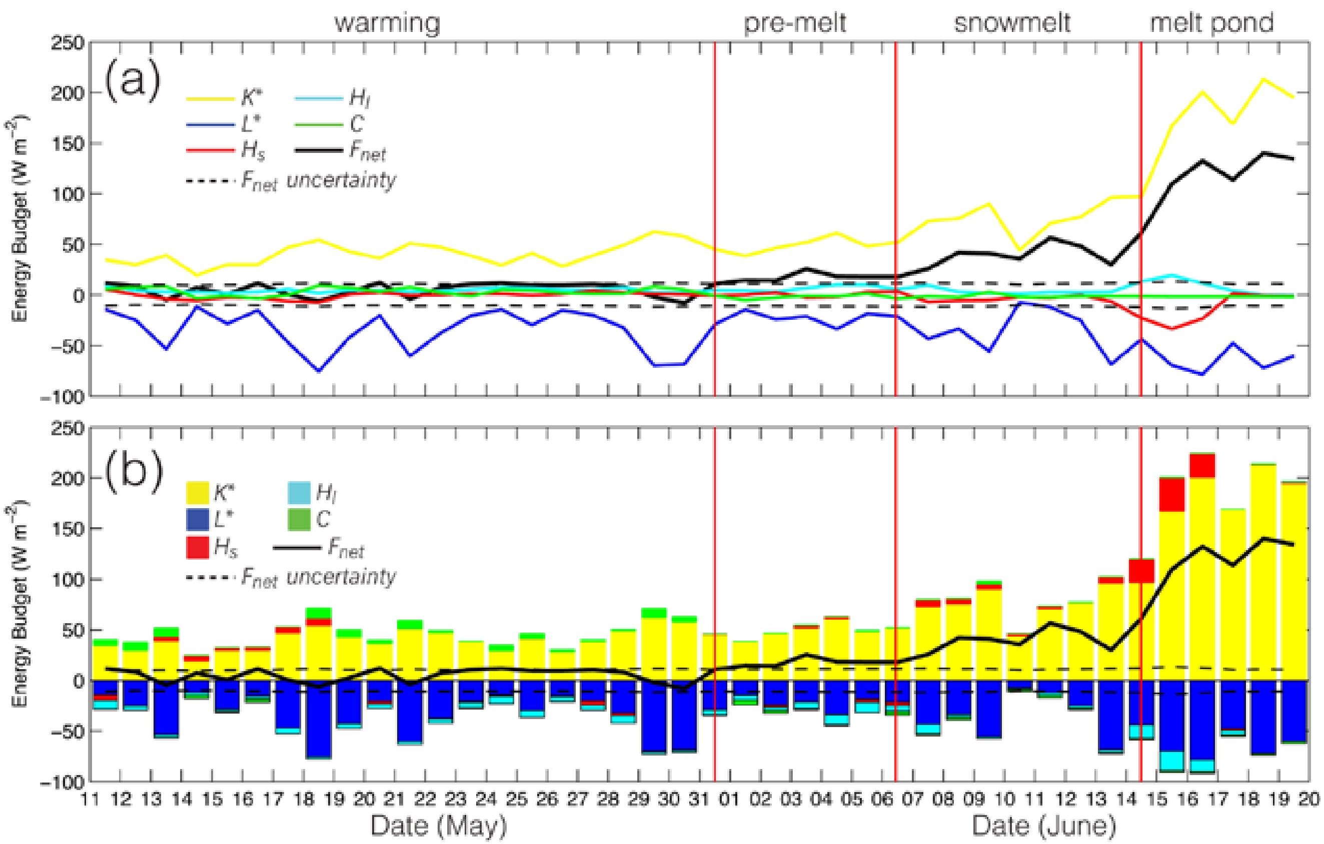

Figure 7. Two representations of the mean daily energy budget terms. In (b) the sign of the turbulent fluxes (H_s and H_l) are reversed from the normal convention so that all sources of energy to the surface are displayed as upwards pointing bars (and vice versa). Red vertical lines are located at the first observations of positive surface temperature (June 1), snowmelt onset (June 6), and melt pond onset (June 14).

were also found at 40 cm. Brine TA_{br} and TCO_{2br} decreased from their maxima on June 4 to 234 and 270 µmol kg^{-1} on June 21 (Figure 9). Two (10 and 17 June) minima in TA_{br} and TCO_{2br} coincided with maxima in nTA_{br} and $nTCO_{2br}$. Melt pond water was also undersaturated with respect to the atmosphere. During the initial formation of melt ponds, their pCO_2 was low (36-84 µatm) but increased to 381 µatm on June 17 before fluctuating between 150 and 370 µatm.

CO_2 fluxes derived from chamber measurements over sea ice were on average at -1.38 mmol m^{-2} d^{-1}. During the initial formation of melt ponds, the fluxes over sea ice peaked at -5.4 mmol m^{-2} d^{-1} on 10 June and -2 mmol m^{-2} d^{-1} on 12 June. Over melt ponds, the initial uptake of CO_2 was significant at -2.9 mmol m^{-2} d^{-1} on 10 June and -4.8 mmol m^{-2} d^{-1} on 12 June. Thereafter the uptake of CO_2 by sea ice and melt ponds decreased over time and stabilized at around -1 mmol m^{-2} d^{-1}.

We also conducted sampling from 10 to 16 March on first-year landfast sea ice in Kapisillit, near Nuuk, Greenland to further explore greenhouse gas dynamics associated with sea ice. The sea ice thickness ranged from 62 to 66 cm. The bulk ice temperature ranged from 3.7°C to 0.8°C with the lowest values in the upper layers. The brine volume fraction profiles were similar to those for bulk ice salinity. For each profile, the brine volume fraction dropped under the permeability threshold of 5% (Golden et al., 1998, 2007) at 25 and at 45 cm indicating that the brine network may not have been fully connected,

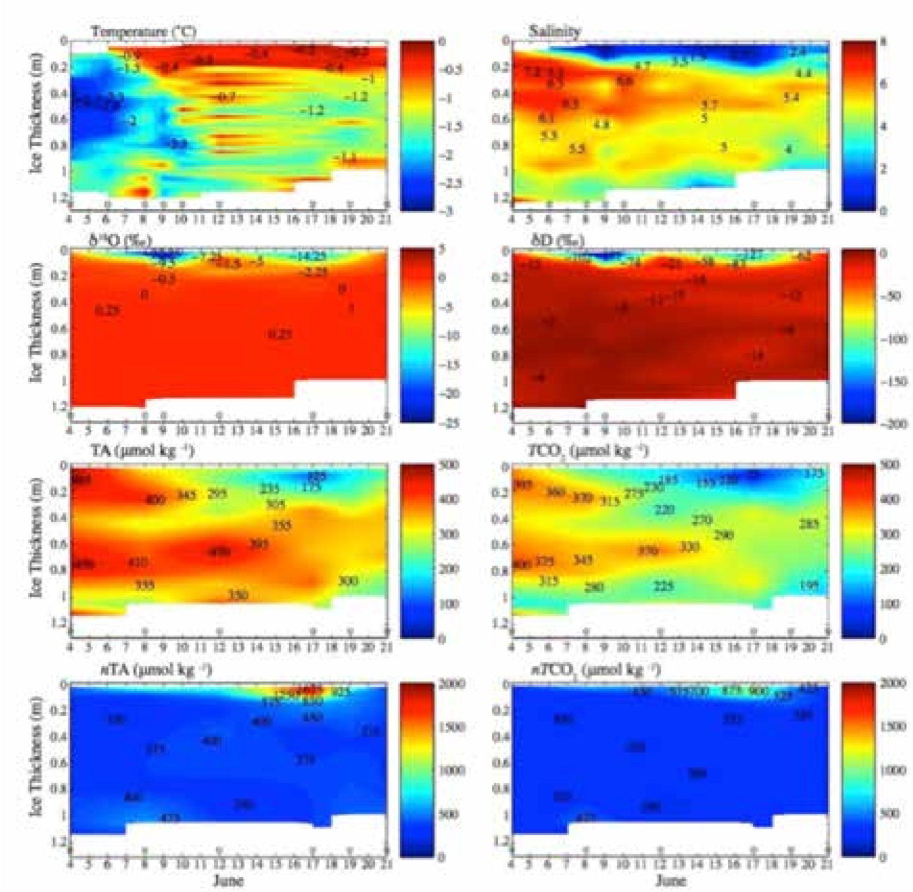

Figure 8. Temporal evolution of sea ice temperature (°C), salinity, isotopic composition of $\delta^{18}O$ and δD (‰), TAice and nTAice (µmol kg^{-1}), TCO_2 and $nTCO_2$ice (µmol kg^{-1}). Open squares on the X-axis mark the sampling dates.

preventing convective internal fluid transport. Isotopic distributions displayed (1) depletion of heavy isotope at the same depth as the drop of the bulk ice salinity was observed (25 cm) and (2) variation in the ice column greater than the maximum allowed by the fractionation coefficients. The fractionation rate depends on the freezing rate and on the thickness of the boundary layer (Eicken et al., 1998, Souchez et al., 1987, 1988). Fractionation coefficients at typical sea-ice growth velocities range from 1.5 and 2.5 ‰, with an equilibrium value (zero growth velocity) of ~ -2.7‰ (Eicken et al., 1998). On 11 and 15 March, the isotopic composition (18 to 26 cm) dropped by 3.7‰ and 3.6‰, changes too large to being explained solely by fractionation process within sea ice.

Total gas content ranged between 4 and 21 mLSTP kg^{-1} ice. A peak in gas content was observed between 25 and 35 cm, where both the bulk ice salinity and the brine volume fraction were at their lowest and where the ice was depleted in $\delta^{18}O$.

Mixing ratios in sea ice ranged from 0.94% to 1.29% (Ar), 22.4% to 32.9% (O_2), and 68.9 to 76.6% (N_2). These correspond to a bulk ice Ar concentration of 1.3–11.7mmol L^{-1} ice, a bulk ice O_2 concentration of 40–275 mmol L^{-1} ice, and a bulk ice N_2 concentration of 57–830 mmol L^{-1} ice. Each gas profile had minimum concentrations in the bottom of the sea ice and a peak around 27 cm below the ice surface. Over time, the O_2, N_2 and Ar gas peaks decreased.

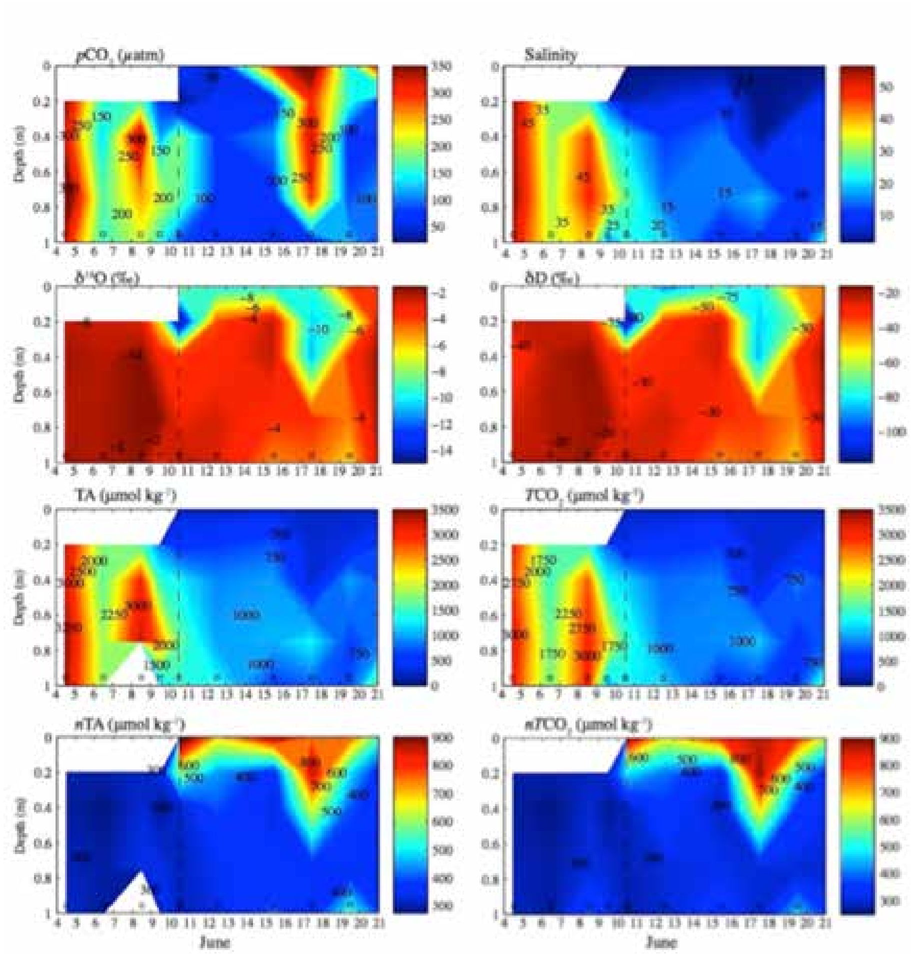

Figure 9. Temporal evolution of brine (0.2, 0.4, 0.75 and 1 m depth) and melt ponds (0 m) pCO_2[in situ](µatm), salinity, isotopic composition of $\delta^{18}O$ and δD(‰), TA and nTA (µmol kg^{-1}), TCO_2 and $nTCO_2$ (µmol kg^{-1}). Open squares on the x-axis mark the sampling dates.

Between 11 and 13 March, O_2 and Ar concentrations decreased by 13.9 and 13.6%, respectively, while N_2 concentrations decreased by 32.1%. More than 70% of the gas species were in the gas phase while less than 30% was dissolved in the brine.

The concentration of dissolved CH_4 in the seawater ranged from 5.7 to 18.4 nmol L^{-1} and the maximum concentrations were measured at the ice-water interface. The bulk ice methane concentration ([CH_4] bulk ice) ranged from 1.8 to 12.1 nmol L^{-1}. The methane part of total gas volume ranged from 3.2 to 28.7 ppmv during the study, with an average value of 11.8 ppmv. The dissolved methane measured in brine ([CH_4]br) ranged from 12.0 to 17.0 nmol L^{-1}.

The pCO_2 of the underlying seawater was slightly undersaturated compared to the atmosphere (390 ppmv) and very under-saturated (77-130 ppmv) compared to seawater at the ice-water interface. The average bulk ice pCO_2 was 194 ppmv, except on 16 March the bulk ice pCO_2 increased from a minimum (<185 ppmv) at the ice bottom to a maximum (>330 ppmv) in the top layers of the ice.

In Else et al. (in review), we examined the potential to measure under-ice turbulent exchanges of heat, salt, momentum, and dissolved oxygen using eddy covariance in an experimental sea ice facility. Over a 15-day period in January 2013, an underwater eddy covariance system was deployed in a large (500 m^3) in-ground concrete pool, which was filled with artificial seawater and exposed to the ambient (-5 to -30°C) atmosphere. Turbulent exchanges were measured continuously as ice grew from 5 to 25 cm thick. Heat, momentum, and dissolved oxygen fluxes were all successfully derived. Quantification of salt fluxes was unsuccessful due to noise in the conductivity sensor, a problem that appears to be resolved by a subsequent version of the instrument. Heat fluxes during initial ice growth were directed upwards at 10 to 25 W m^{-2} suggesting interesting double-diffusion effects. Dissolved oxygen fluxes were directed downwards at rates of 5 to 50 mmol m^{-2} d^{-1} throughout the experiment, at times exceeding the expected amount of oxygen rejected with the brine during ice growth. Bubble formation and dissolution was identified as one possible cause of the high fluxes. Momentum fluxes showed interesting correlations with ice growth and melt, but were generally higher than expected. We concluded that with the exception of the conductivity sensor, the eddy covariance system worked well, and that useful information about turbulent exchanges under thin ice can be obtained from an experimental sea ice facility of this size.

Sea Ice-Associated Biology

The bottom 5 cm of sea ice in Dease Strait was characterized by low bacterial (max. 0.2 µmol C L^{-1} H^{-1}) and primary productivity (max. 15 µmol C L^{-1} H^{-1} at approximate in situ light conditions) throughout the spring. Chl *a* levels increased from March to June until reaching a maximum of approximately 300 µg L^{-1}, but were also low for the region (e.g. Arrigo et al., 2010). The termination phase of the ice algae bloom marked by a decline in chl *a* was not observed in our study due to a number of late-spring snowfall events that delayed the bloom peak. These trends in chl *a* applied to both high and low snow covers which were found to be statistically identical. Preliminary results indicate diatoms of the genus *Attheya* rather than *Nitzschia* dominated the ice algal community for most of the spring. We also observed increasing abundances of choanoflagellates with progression of the season.

In Else et al. (2014b), we present underwater eddy covariance measurements of dissolved oxygen, heat, salt, and momentum fluxes under landfast sea ice in Dease Strait in late winter/early spring (Apr. 20-May 5, 2014), revealing interesting insights about this key transition period. We observed a downward flux of salt (desalination of the ice) throughout the period, which followed a distinct diurnal pattern where the strongest fluxes occurred at night. Heat flux also followed a diurnal pattern, with energy being transferred from the ocean to the ice at night, and vice versa during the day. Oxygen fluxes were persistently directed upwards, in contrast to the expected autotrophic nature of the under-ice community during this time period. Preliminary analysis suggests that diurnal patterns strongly affect under-ice processes during this time period. Synoptic scale weather patterns also appear to influence the under-ice environment in some way.

Contaminants

We have calculated meltwater equilibrium concentrations (CEq), meltwater near-equilibrium concentrations (CNeq, actual concentrations that will be reached over the duration of pond coverage), and melt pond enrichment factors (MEFs), defined as CNeq divided by seawater concentration, for selected legacy OCPs and CUPs in the Beaufort Sea and Amundsen Gulf in May-July 2008. Predicted concentrations in melt pond water are relatively high for all of the CUPs compared to legacy OCPs, ranging from 27 ± 28 pg·dm^{-3} for dacthal to 258 ± 443 pg·dm^{-3} for chlorothalonil, and from 0.7 ± 0.4 pg·dm^{-3} for trans-chlordane to 41 ± 18 pg·dm^{-3} for dieldrin. The average duration of pond coverage in the Beaufort Sea of 35-58 days will allow for all of the OCPs and CUPs analyzed in this study to reach over

70% of equilibrium concentration with an exception of chlorothalonil, which will approach only 10-20% of CEq due to its relatively low HLC. Modeling of air-water exchange dynamics assumes no supply of contaminants from the melting snow at the beginning of spring melt and no wet atmospheric deposition, a rather unrealistic scenario; however, the one we chose due to its conservative nature. In reality, we think that the melt ponds should reach the equilibrium partitioning with air considerably faster.

DISCUSSION

Physical Oceanography

Ice formation combined with continuous removal of ice by northerly winds makes the polynya area near the mouth of Young Sound very efficient at providing salt to the underlying water. On the fjord-side of the sill (Figure 2a), the gravity current of dense, brine-enriched water supplies the interior of the fjord with cold, saline and oxygen enriched water. The m02 bottom temperature time series shows that events of potential supercooling alternate with relatively warm events during which temperature exceeds potential temperature of freezing by 0.03-0.08°C, suggesting episodic inflow of relatively warm and saline Atlantic-modified shelf water above the entrance sill. The down-fjord wind creates open water over the mouth of Young Sound and favors upwelling on the shelf-side of the sill. The wind-driven upwelling of saltier, relatively warm Atlantic waters up to the sill depth combined with cross-sill tidal flow can transport slightly warm and saline water into Young Sound, generating episodic “warm conditions” following down-fjord wind events. However, oxygen supersaturation in the Young Sound intermediate layer clearly identifies brine from ice growth within the polynya as its primary source.

The difference in salinity in Young Sound between October 2013 and May 2014 indicates salinity adjustment to winter sea ice formation assuming there is only salt water influx to Young Sound over the entrance sill compensating for the sea-ice outflow from the polynya. A simple balance model shows that depending on the brine release catchment area, 11.1-93.5 m of total ice growth is needed explain the observed salt content increase in Young Sound.

A critical factor determining the ability of the ocean to affect ice growth is the water column heat content prior to the onset of freeze-up. Another factor that may strongly affect the ice thickness is the irregularity of snow thickness altering the bulk snow thermal conductivity.

We examined the ocean heat flux inferred from (i) the comparison of measured and modeled ice growth rates, and (ii) bulk turbulent parameterization. Both methods provide comparable fluxes between 0 and 100 W m^{-2} in inner Young Sound. The total amount of heat transferred from the ocean to sea ice in the inner fjord is 108 MJ m^{-2} ; in the outer fjord it is 157 MJ m^{-2} during winter. The result is considerable horizontal redistribution of heat in Young Sound during winter, including its export to the open ocean. Heat fluxes in the inner fjord gradually decreased from freeze-up to the end of the observational period, whereas heat fluxes at the outer fjord declined considerably after the first 50 days.

Drastic changes occurred on December 26 after strong northerly winds forced the polynya at the mouth of Young Sound to open and caused the landfast ice edge to retreat inside the fjord ~3.5 km behind the entrance sill. The combination of wind-driven surface outflow and downwelling at the shelf-side of the sill associated with dense water formation in the polynya further amplified the circulation cell followed by increased heat content in the surface layer in the outer fjord. In the inner fjord, the reinforcement of surface outflow during the polynya opening did not significantly intensify the ocean heat flux.

Sea Ice Physical Properties and Processes

The morphology of brine drainage channel features is instructive to sea ice biogeochemical cycling due to the size of the individual channels and their connection to the seawater below. In particular, brine supersaturated with CO_2 (Papadimitriou et al., 2004), may lead to the precipitation of ikaite crystals (Rysgaard et al., 2012, 2014). CO_2 released by ikaite precipitation may be rejected to the water column due to impermeability of sea ice above this zone (e.g. Loose et al., 2011), potentially explaining under-ice increases in pCO_2 to near-saturation during winter observed by Else et al. (2012). Much of the young ice we sampled was cold enough (<-2.2 °C) to produce ikaite crystals, and the observed brine drainage channel feature may offer them a mechanism by which to descend into the seawater taking their CO_2-equivalent with them. Low concentrations of ikaite near the sea ice bottom observed by Geilfus et al. (2013a) may therefore be due to either the lack of crystal formation or ikaite crystal export to the water column. The attending channels to the main brine drainage channel range from 0.8 to 1.5 mm in diameter, which is greater than the ikaite crystal sizes of <0.1 mm to 1 mm reported by Rysgaard et al. (2012) in Arctic sea ice, consistent with work showing that ikaite removal from sea ice through brine drainage is a process affecting the alkalinity of under-sea ice seawater and consequently affects ocean-atmosphere CO_2 exchange.

Sea Ice Biogeochemical Cycling

Early in the melt period, increased ice temperatures and subsequent decreased bulk ice salinity and dissolution of ikaite crystals decreased TA, TCO_2 and pCO_2 in bulk sea ice and brine. The decrease of pCO_2 causes sea ice to act as a sink for atmospheric CO_2, especially during the initial formation of melt ponds due to their very low pCO_2 levels. The percolation of melt pond water into the ice matrix further dilutes brine, decreasing its TA, TCO_2 and pCO_2. As temperature rises, melt water is continuously supplied to the ponds, which prevents melt ponds from fully equilibrating with the atmospheric CO_2. Instead, melt pond pCO_2 fluctuates between 0 µatm and the atmospheric concentration, but since melt ponds are continuously supplied with fresh melt water while simultaneously draining to the ocean, their in situ pCO_2 remains undersaturated promoting a continuous but moderate uptake of CO_2 from the atmosphere (~ -1 mmol m^{-2} d^{-1}). We estimate the CO_2 flux due to melt ponds in the Arctic to be on the order of -7 to -16 Tg of C. This is 5-15 % of the total uptake for the Arctic Ocean previously reported (Bates and Mathis, 2009; Takahashi et al., 2009).

We also investigated gas transport in natural sea ice in the absence of brine convection. Low average bulk ice salinity induced a stratified brine network, which prevented convective exchanges between the ice, water, and atmosphere, making transport of gas species mainly diffusive or due to buoyancy. Based on the total gas content, the bulk ice concentration of O_2, N_2, and Ar, and the gas-filled porosity, we conclude that gas species are preferentially located in bubbles. The gas incorporation at the ice-water interface occurred close to the atmospheric solubility value, and the gas-filled porosity was close to zero in the bottom of the ice so nucleation occurred mainly in brine. Bubble nucleation requires supersaturation of dissolved gas in brine; nucleation was observed once the concentration exceed 2.7 times the atmospheric saturation. This level of supersaturation is in agreement with previous work on bubble nucleation in sea ice (e.g. Killawee et al., 1998). Our computed transport rates were for a narrow range of total porosity (4 to 8%), so it was not possible to ascertain a relationship between porosity and the diffusion coefficient (D). Although most gases were located in bubbles, the effective diffusivities for O_2, Ar and N_2 were close to the aqueous diffusion rate ($\approx 10^{-5}$ cm^2 s^{-1}). The preference for gases to exist in bubbles does not exclude aqueous diffusion through brine. The majority of bubbles observed by Light et al. (2003) were contained within brine inclusions. We hypothesize that nucleation occurs in the brine network and the gas-filled inclusions are able to exchange with the brine and diffuse into the aqueous phase (after Loose et al., 2011). Finally, the preferential partitioning of N_2 into gas-filled pore spaces within the ice could produce a greater apparent diffusion rate compared to O_2 and Ar, as well as a larger rate of incorporation at the ice-water interface during freezing.

We conclude that sub-arctic sea ice can be a sink for atmospheric CO_2, while being a source of CH_4. Freshwater runoff from land influenced sea ice formation, as a thin freshwater layer at the sea ice-water column interface was evident. This caused deviation from the traditional C-shaped ice salinity profile and depleted heavy isotopes. The freshwater caused increased buoyancy and currents velocities at the sea ice-water interface, accelerating the nucleation processes in the boundary layer and increasing the total gas content of the ice. The partial pressure of CH_4 exceeded the atmospheric CH_4 content making sea ice a potential source of CH_4 to the atmosphere. When sea ice forms, CH_4 can accumulate within or below the sea ice, and when the ice breaks up and melts during spring and summer, large CH_4 fluxes to the atmosphere could be expected. During sea ice break-up, Gosink and Kelley (1979) and Shakhova et al. (2010) observed increased CH_4 concentration in the atmosphere above sea ice as well as in surface seawater. Sea ice provides an interface in which the methane could be stored and transformed over time by biogeochemical processes. Further studies based on longer times series and carbon isotope signatures of CH_4 will provide us the opportunity to study the potential methane oxidation rate within sea ice; i.e. sea ice could provide a layer at the ocean surface where CH_4 is degraded creating a sink for oceanic CH_4.

Sea Ice-Associated Biology

Low productivity estimates through spring, along with the similarity between chl *a* under low and high snow covers indicates that light availability was not the limiting control on ice algae population. We hypothesize that low nutrient availability in the area limited production, and we will be investigating this notion further following the processing of our nutrient samples. We also speculate that low bacteria productivity was influenced by the persistence of a significant choanoflagellate grazer community.

Although bacterial and algal productivity were low, a switch from net heterotrophy to net autotrophy was observed between March and April using a new oxygen optode incubation technique. This change was driven by the increase in algal abundance in spring relative to bacteria, which remained relatively constant. We also used this optode technique to calculate measurements of gross production, which compared very well with gross primary production estimates derived from 14C methods. The success of optode use in our study may validate the technique as an alternative to traditional radioisotope measurements. This represents a particularly important finding for Arctic research given the difficulties encountered with radioisotope use in remote field locations.

Contaminants

The process of atmospheric loading of contaminants to surface meltwater and subsequent drainage to the Arctic Ocean can be described as a ‘pump’ that transfers contaminants from the atmosphere to an ice-covered ocean via pond meltwater (Figure 10). To determine the significance of this contaminant input route to the Arctic Ocean, we calculated the total quantity of various CUPs that would be delivered to the surface seawater of the Beaufort Sea in 2008 via melt pond leakage into the ocean compared to the standing stock of CUPs held in the mixed layer of the Beaufort Sea. The total amount of CUPs discharged to the Beaufort Sea with surface meltwater drainage in 2008 was calculated to be 6 kg for dacthal, 16 kg for chlorpyrifos, 6 kg for endosulfan I, and 54 kg for chlorothalonil. The hypothetical contaminant ‘pump’ could, therefore, deliver annually about 2% of dacthal, 4% of chlorpyrifos, 10% of endosulfan I, and 4% of chlorothalonil relative to the standing stock in the Polar Mixed Layer (40 m).

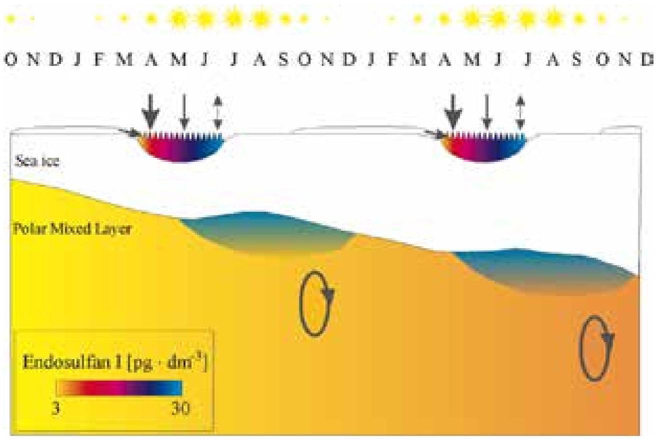

Figure 10. Hypothetical contaminant pump function schematic using endosulfan I as an example, colors denote endosulfan I concentrations in melt ponds and seawater.

CONCLUSION

Physical Oceanography

The lack of circulation and corresponding water flushing during winter in Young Sound was due to sea ice that eliminated wind stress and wind-driven circulation. We show that a polynya, created by wind forcing over the mouth of Young Sound in December 2013-March 2014, facilitates water circulation in the landfast ice-covered fjord, supplying the fjord interior with cool, saline and oxygenated water. During winter 2013-14 a gravity current of dense and brine-enriched polynya-modified water enhances the inflow of water between 40 and 140 m to the interior of the fjord with a corresponding outflow in the surface layer.

Atmospheric heating and vertical mixing during summer allowed the upper 150 m of Young Sound to accumulate heat throughout summer. A portion of this heat was lost during fall, but by the end of October 2013, between 213 and 407 MJ m^{-2} remained in the water column and would contribute to retarding ice growth throughout winter. Enhanced circulation during the polynya event caused the ocean heat flux to be twice as great at the outer fjord than in the inner fjord. This heat is most likely associated with entrainment of warm intermediate waters to the surface layer by enhanced vertical mixing. Therefore, the ocean heat flux within Young Sound seems to be preconditioned by water dynamics that strongly depend on wind forcing and particularly the position of the landfast ice edge relative to the entrance sill of the fjord.

Sea Ice Physical Properties and Processes

A brine channel in young sea ice may be imaged using Magnetic Resonance (MR) in three-dimensions in as little as 4 minutes 30 seconds. Brine drainage channels may be established concurrent with ice growth. Three-dimensional MR images may be used to compute accurate vertical profiles of sea ice liquid volume fraction.

Frost flowers are formed by deposition of vapour provided by liquid brine skim on the surface of the sea ice. The liquid brine skim is the result of upward brine expulsion from the sea ice as it cools and brine volumes contract. Frost flowers formed during very low wind speeds and negative net radiation balance at the surface. A substantial difference in temperature was observed between the colder frost flowers and the warmer mean sea ice surface. This temperature difference decreased with frost flower age/height. Frost flower degradation is associated with a surface net radiation balance equal to zero, which caused them to sublimate. Sublimation was enhanced by increased wind speeds and decreased relative humidity.

Sea Ice Biogeochemical Cycling

By analysing the temporal evolution of an internal gas peak within the ice, we deduced the bulk gas transport coefficients for oxygen (DO^2), argon (DAr) and nitrogen (DN^2). The values fit to the few existing estimates from experimental work, and are close to the diffusivity values in water (10^{-5} cm^2 s^{-1}). These results indicate there was no convective transport within the sampled sea ice at this location; the transport of gas by diffusion through brine, either in the liquid or gas phase.

Fjord systems, characterized by freshwater runoff and riverine input based on $\delta^{18}O$ data, result in fresher sea-ice layers with higher gas content than is typical from marine sea ice. The bulk ice [CH_4] partial pressure was markedly higher than the average atmospheric methane content. Evidently most of the trapped methane within the ice was contained inside bubbles, and only a minor portion was dissolved in brine. The bulk ice pCO_2 indicated that sea ice above -4°C is under-saturated compared to the atmosphere. This study adds to the few existing studies of CH_4 and CO_2 in sea ice, and we conclude that subarctic sea can be a sink for atmospheric CO_2, while being a source of CH_4.

Sea Ice-Associated Biology

Our study is an important step towards understanding the seasonal and spatial variability in sea ice productivity across the Arctic. The location of these measurements will also contribute to the baseline of future studies in the area that are likely to occur with the development of the Canadian High Arctic Research Station (CHARS) in Cambridge Bay.

Contaminants

The ongoing transition from perennial to annual ice is changing the role of sea ice in contaminant pathways; FYI contains more brine and contaminants, and thus is much more efficient in the delivery of contaminants to the Arctic food web via exposures to ice-associated biota compared to MYI. FYI experiences high growth rates at the beginning of its annual life cycle, while MYI growth rates are much slower due to the insulating effect of the existing ice and/or snow cover. With an increasing percent coverage of the Arctic by FYI relative to MYI, a hypothetical contaminant pump will be turned on over vast areas of the Arctic Ocean with as of yet poorly understood consequences. Transition towards a FYI-dominated summer Arctic may, therefore, result in over 40% increase of efficacy of the melt pond hypothetical contaminant 'pump' due to complete melting of ice each year, and a greater volume of meltwater due to higher air temperatures and increased precipitation. In such a scenario the importance of atmospheric deposition of organic contaminants to the surface meltwater will depend on the length of time meltwater will have to accumulate contaminants from the atmosphere before complete thawing takes place, again, a climate change parameter of significance.

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EFFECTS OF CLIMATE CHANGE ON CONTAMINANT CYCLING IN THE COASTAL AND MARINE ECOSYSTEMS

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ABSTRACT

Contaminants pose a potential hazard to Arctic fish and marine mammal health, and ultimately to northerners that consume the tissues of these animals as part of their traditional diets. It is therefore imperative that we strive to understand how climate variability in physical forcing and the biogeochemical response to this primary forcing will affect among others 1) contaminant transport processes and cycling; 2) biomagnification through Arctic marine food webs; 3) foraging behaviour of marine mammals (e.g. in response to changing sea ice regimes); 4) changes to hunting patterns and diets of northerners to reflect availability of traditional foods (e.g. less ice may lead to reduced reproductive success of ringed seals forcing northerners to consume more beluga tissues which typically have 10- fold higher contaminant concentrations). Overall, results from our research will help assess the vulnerability of coastal Inuit communities to climate change, document and project impacts of climate change on traditional food security and community health and provide the information required by communities, scientists and policy makers to help develop adaptation strategies. Our findings will help to test and shape the policy for the future management of contaminants emissions and long-range transport to the Arctic and will support integrated ocean management programs such as Marine Protected Areas and Large Ocean Management Areas (MPA and LOMA, respectively) such as zone 1(a)s in the Beaufort Sea.

KEY MESSAGES

Transport and transformation of mercury across the ocean-sea ice-atmosphere (OSA) interface

- Mesocosm-based study at the Sea-ice Environmental Research Facility (SERF) confirms our previous field observation that entrainment of particulate matter within frazil ice crystals during ice formation is the major process of mercury incorporation into newly formed sea ice.
- Measurement of bromide and chloride in snow and sea ice at a coastal Arctic site shows that surface or blowing snow is the major site for bromine activation and the subsequent atmospheric mercury depletion.
- Sub-surface production of methylmercury in seawater appears to be ubiquitous in the Canadian Arctic Ocean at a water depth of ~150 m, although the ratio of methylmercury to total mercury is more variable in the Canadian Arctic Archipelago and Baffin Bay.

Hg isotope ratios in arctic environments

- Hg isotope ratios are potentially useful to identify sources of Hg to the Arctic.
- Measuring Hg isotope fractionation will add to our understanding of the cycling of Hg in remote marine environments.

Distant drivers or local signals: Where do mercury trends in western Arctic belugas originate?

- We present a 31-year time series for mercury in beluga whales from the Beaufort Sea.
- A large peak in beluga Hg concentration in the late 1990’s remains a key feature.
- Neither diet nor trends in Hg emissions can explain beluga Hg trends.
- The Pacific Decadal Oscillation, lagged by 8 years, provides the best correlation with beluga Hg.
- Beluga Hg trends may reflect distant drivers of climate variability that likely altered dietary exposure in their home range.

Linking the carbon and mercury cycles in the Beaufort Sea using a seasonal, one dimensional water column model

- A dynamic model is being developed and refined that describes the speciation and fate of mercury in relation to the cycling of organic carbon in the upper water column (120 m) of the Beaufort Sea in order to help us gain a more comprehensive understanding of the system and allow us to explore the potential impacts of climate change on mercury cycling.
- Initial model results are in good agreement with total Hg (HgT) concentrations in seawater and zooplankton measured previously in the same area but also highlight the need for more research on the seasonal rates of mercury methylation and demethylation.
- Results from preliminary climate change modeling scenarios suggest that a longer open water period and modest increase in primary production will enhance losses of Hg to the

atmosphere by evasion and slightly increase the Hg flux to deeper waters with settling particles.

The composition ($\delta^{13}C$, $\Delta^{14}C$ and lignins) of organic matter transported by rivers to Hudson Bay

- Highest concentrations and fluxes of organic carbon (OC) and lignin phenolics to Hudson Bay enter in the southwest sector, especially from the Nelson River.
- The majority of the OC (~90%) is in the dissolved phase.
- Specific lignin markers (ratios of vanillyls, syryngyls and cynamyls (S/V and C/V) show a greater prevalence of woody (gymnosperm) carbon in the south giving way to more non-woody (angiosperm) sources in the north reflecting tundra.
- Most of the POC and DOC transported by rivers is partially degraded material exhibiting relatively young (<500 years) $\Delta^{14}C$ ages.
- The age and composition of OC presently transported in Hudson Bay Rivers provides a baseline from which to evaluate future change either in permafrost thaw (releasing older material) or in vegetative change (woody shrubs invading tundra).

Spatial, temporal, and source variations of hydrocarbons in marine sediments from Baffin Bay, Eastern Canadian Arctic

- Data from surface and historical sediments from each sediment core are given.
- Current hydrocarbon levels are within a factor of 10 of pre-industrial sediments.
- Petrogenic PAH sources to the region are predominate.
- The results are a preliminary characterization of the hydrocarbons in this region.

Analysis of Polycyclic Aromatic Hydrocarbons in benthic invertebrates from Baffin Bay

- The modified QuEChERS method in combination with silica gel chromatography has provided for a Quick, Easy, Cheap, Efficient, Rugged and Safe method to extract Polycyclic Aromatic Hydrocarbons (PAHs) from biological tissues.
- The highest concentrations of PAHs measured in benthic invertebrates were well below the levels generally giving rise to measurable physiological and ecological effects.
- *Gorgoncephelus arcticus* had the highest concentrations of benzo[a]pyrene giving rise to the highest TEQ (Toxic Equivalent) values.
- Biota-sediment accumulation factor (BSAF) values are the highest for *Ctenodiscus crispatus* and reflect the ecological (mode of feeding) and physiological characteristics of individual species (PAH metabolism by *Gorgoncephelus arctics*/*Psilaster andromeda* but not *Ctenodiscus crispatus*).

Twenty years of air-water gas exchange observations for pesticides in the western Arctic Ocean

- Legacy organochlorine pesticides are out-gassing from the Arctic Ocean water and have become a secondary source to arctic air where Canadian archipelago water is a continuing sink for currently used pesticides.

The delivery of contaminants to the Arctic food web: why sea ice matters

- Sea ice may facilitate the delivery of organic contaminants to the Arctic marine food web.
- Organic contaminants may be concentrated in brine, under-ice seawater, and melt ponds.
- CUPs pose a particular risk of increased exposures via dry deposition to melt ponds.
- Dry deposition to melt ponds is likely an important loading route of selected CUPs to the Arctic Ocean.

IRIS 1 – western and central high Arctic

- The IRIS 1 Regional Impact Assessment is nearing its 3rd and final draft and will be published in 2015.
- The IRIS 1 leader and coordinator have been engaged in the Adaptation Actions for a Changing Arctic (AACA) project undertaken by AMAP, specifically as participants in the Barents/Chukchi/Beaufort seas assessment.

OBJECTIVES

Transport and transformation of mercury across the ocean-sea ice-atmosphere (OSA) interface

- To understand the role of sea ice in the occurrence of atmospheric mercury depletion events.
- To understand and quantify the processes by which mercury is transported from the atmosphere to the ocean via the dynamic sea ice environment.
- To examine and quantify the sources of methylmercury in Arctic seawater.

Hg isotope ratios in arctic environments

- To develop a method for pre-concentration of large volumes of seawater for Hg isotope ratio measurements.
- To characterize the spatial variations in Hg isotope ratios in arctic seawater.
- To identify sources of Hg in artic environments (sediment, water, biota).

Distant drivers or local signals: Where do mercury trends in western Arctic belugas originate?

- To examine Hg concentrations in beluga muscle and liver tissue over the 31 year time period and ask the question “Which major drivers might be linked to these observed trends?”
- To consider the direct impact of dietary Hg exposure as evident in beluga stable isotope data.
- To examine the potential of indicators of climate variability (e.g., the Arctic Oscillation (AO), Pacific Decadal Oscillation (PDO)) to explain the observed Hg trends.

Linking the carbon and mercury cycles in the Beaufort Sea using a seasonal, one-dimensional water column model

- To develop and calibrate a comprehensive dynamic mercury speciation and fate model for the Beaufort Sea ecosystem that is responsive to climate-related drivers and links atmospheric mercury inputs to the carbon cycle and entry into the base of the marine food web throughout all seasons.

- To use the model to identify and prioritize knowledge gaps that can be addressed by further field studies, and to explore the potential impacts of climate change on mercury cycling and fate in marine ecosystems.

The composition ($\delta^{13}C$, $\Delta^{14}C$ and lignins) of organic matter transported by rivers to Hudson Bay

- To measure the modern composition and concentration of organic carbon in 17 Hudson Bay Rivers.
- To determine the flux of organic carbon (dissolved and particulate) to Hudson Bay to provide a constraint for organic budgets for the Hudson Bay System.
- To determine the present sources and the state of degradation of the organic carbon using specific lignin biomarkers.
- To determine age of the organic carbon (dissolved and particulate) and thereby infer drainage basin soil processes involved in supplying the organic carbon to rivers.

Spatial, temporal, and source variations of hydrocarbons in marine sediments from Baffin Bay, Eastern Canadian Arctic

- To establish the composition and concentrations of hydrocarbons in surface and historical sediments from eleven sites across northern Baffin Bay, prior to oil and gas exploration/ exploitation in the area.
- To provide an assessment of 1) the geographical variability of current hydrocarbon concentrations in this region; 2) predominant sources of hydrocarbons based on their composition; and 3) whether recently accumulated sediment (post-industrial) differs from older (pre-industrial) sediment.

Analysis of Polycyclic Aromatic Hydrocarbons in benthic invertebrates from Baffin Bay

- To establish baseline levels of petroleum hydrocarbons in the Baffin Bay's sediments, water and food web.
- 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 and increased shipping.

Twenty years of air-water gas exchange observations for pesticides in the western Arctic Ocean

- To determine the air-water gas exchange direction and magnitude for legacy and currently used pesticides in the Canadian Archipelago.

The delivery of contaminants to the Arctic food web: why sea ice matters

- To describe the role sea ice plays in the delivery of various OCPs and CUPs to marine food webs.
- To model organic contaminant concentrations in melt ponds in the Beaufort Sea area based on the measured concentrations in seawater and air.
- To describe how the rate of ablation and subsequent ponding mechanisms control contaminant exchanges between melt ponds and atmosphere.

- To predict how changing sea-ice conditions in the Beaufort Sea, namely a shift from perennial towards annual ice types, may affect loading of organic contaminants to the Arctic Ocean via dry deposition to melt ponds and subsequent flushing.

IRIS 1 – western and central high Arctic

- To review the 2nd draft of the assessment.
- To acquire NEMO (oceanographic projections) results from David Barber's group at the University of Manitoba.
- To provide review comments and NEMO output to authors for revisions.
- To provide revised chapters to a local publisher to professionally compile the materials into a book for printing.
- To have a print version of the assessment for the Arctic Change 2014 conference in December.
- AACA – Objectives relating to the BCB assessment consisted of participating in teleconferences and writing workshops, and providing support and resources as needed.

INTRODUCTION

Transport and transformation of mercury across the ocean-sea ice-atmosphere (OSA) interface

Evidence is now mounting that the highly variable mercury concentrations in Arctic marine mammals in recent decades are no longer a simple function of external, anthropogenic mercury emissions; instead, they are increasingly driven by climate-induced changes in post-depositional processes that control the transport, transformation, and biological uptake of stored mercury in the Arctic Ocean (AMAP, 2011; Wang et al., 2010). We have recently shown that the sea-ice environment plays a major role in controlling the magnitude and timing of atmospheric mercury flux to the underlying marine ecosystem (Burt et al., 2013; Chaulk et al., 2011; Chaulk, 2011). We have also shown a profound production zone of methylmercury in sub-surface seawater in Beaufort Sea (Wang et al., 2012), and potential methylmercury production in the Arctic multi-year sea ice (Beattie et al., 2014). However, major uncertainties exist with respect to the mechanism by which sea ice affects the net atmospheric transport of mercury, and the process responsible for methylmercury production in seawater and sea ice.

Hg isotope ratios in arctic environments

In some arras of the Arctic, levels of mercury continue to increase in food-webs, while concentrations seem to level off in other regions. However, we are still unable to easily resolve sources to the Arctic and distinguish between natural and anthropogenic sources of mercury, which would be a prerequisite for an effective management of Hg in polar regions. While Hg emissions from Europe and North America declined over the past 20 years (Pacyna et al., 2006), emissions from Asia increased. Biswas et al. (2008) suggested that coal deposits within the United States, China, and Russia-Kazakhstan, which are three of the five greatest coal-producing regions, all have unique Hg isotope signatures that may be used to differentiate the various Hg sources. For example, Carignan et al. (2009) measured Hg isotope ratios in lichens, assuming it would represent the composition of atmospheric Hg. They also concluded that Hg isotope signatures may be used to trace globally relevant sources and pathways of Hg. Therefore, we suggest to use this still relatively new tool of Hg isotope fingerprinting to characterize representative samples from the arctic (water, sediment, biota) to identify similarities and potentially identify pathways of Hg in polar regions. While measurements of Hg isotope ratios in the environment are increasing information regarding polar environments is still extremely scarce. We believe that Hg isotope ratio measurements in arctic samples will be invaluable to determine the sources of Hg to the Arctic.

Distant drivers or local signals: Where do mercury trends in western Arctic belugas originate?

The interaction among external drivers (environment, ecology), emission sources and processes intrinsic to belugas (physiology, behavior) combine to produce the Hg trend observations. Given our improved understanding of system and biological processes we assess the recent temporal trends in beluga Hg concentrations while considering confounding factors such as age and size between tissue groups to address key drivers of trends. Since 2002 (Lockhart et al., 2005), an additional 10 consecutive years of beluga data have been collected, yielding 18 points in time between 1981 and 2012 where Hg, biological data and diet metrics have been recorded. During this time span, Hg emissions have continued to increase at an annual rate of 1.3% (Muntean et al., 2014). Additionally, significant changes in the Arctic Ocean and surrounding drainage basin have been observed and documented in numerous publications with most of these changes linked to declining ice.

Linking the carbon and mercury cycles in the Beaufort Sea using a seasonal, one-dimensional water column model

While efforts to reduce mercury emissions in recent decades have generally lead to gradual declines in global atmospheric concentrations, including in the Arctic (Li et al., 2008), concentrations in some Arctic biota and in sediments have either not declined or have increased (Outridge et al., 2008; Carrie et al., 2010). This disconnect between trends in air and those in sediments and biota has led to the hypothesis that climate change is altering the cycling of the existing mercury inventory already in the Arctic, and that these changes outweigh the changes in mercury inputs to the system (Macdonald et al., 2005; Macdonald et al., 2008; Outridge et al., 2008; Carrie et al., 2010). Potential climate-related mechanisms that could alter mercury cycling in the Arctic marine ecosystem include: changes in sea ice cover affecting air-water exchange of mercury; changes in ice cover, light regime and nutrient supply altering food web structure, primary production and the vertical flux of organic carbon and particle-bound mercury. In turn, these may affect the production or concentration of mono-methylmercury that biomagnifies through the food web. This is supported by recent studies that have linked Hg methylation rates with primary productivity and organic carbon remineralization in mid-depth seawaters near the oxygen minimum (Cossa et al., 2009; Sunderland et al., 2009; Wang et al., 2012; Blum et al., 2013; Pućko et al., 2014).

The composition ($\delta^{13}C$, $\Delta^{14}C$ and lignins) of organic matter transported by rivers to Hudson Bay

Climate change in polar seas is most commonly thought of as change in sea-ice conditions, and there is an accumulating body of evidence that multi-year ice in the Arctic Ocean is being replaced by seasonal sea ice (e.g., ACIA (2005)). Hudson Bay presently exhibits a complete cryogenic cycle, losing all of its ice by the end of each summer. Therefore, for Hudson Bay we may expect the leading manifestation of change to occur in the length of time of open water as recorded from space. However, change in the organic systems of polar seas is also of great concern (Stein and Macdonald, 2004), both for the potentially large effect on ecosystems and carbon sequestration, and for the opportunity to access archived records of change in polar ocean sediments. Given the large encompassing drainage basins for the Arctic's oceans and seas, much of the change occurring in the ocean does not necessarily relate to sea ice but rather to imported carbon from adjacent land areas and coastal sea. In this context, Hudson Bay likely provides an exceptionally good sentinel for the Arctic Ocean in that it is 1) strongly influenced by its drainage basins, 2) rivers entering Hudson Bay provide a large component of the organic matter supply, 3) the drainage basins spans areas that are dominated by woody vegetation and soils not subject to permafrost in the south to tundra and permafrost domination in the north, and 4) given its location to the south of the Arctic Ocean, Hudson Bay is already undergoing transitions ahead of the Arctic Ocean (Macdonald and Kuzyk, 2011). Accordingly, this region likely provides an excellent proxy sea to evaluate how permafrost thaw and vegetative change will manifest themselves in the adjacent ocean implying, importantly, that the ocean sediments and water may provide evidence of integrated change in the surrounding basins. In previous papers (Kuzyk et al. (2008, 2009, 2010, 2011) we have applied Hudson Bay sediments to the task of inferring inputs and sources of particulate organic carbon to Hudson Bay by creating budgets and measuring biomarkers like lignins. These approaches were insightful and provocative, but they clearly indicated to us the need to collect samples from a suite of Hudson Bay rivers to determine directly the modern input of terrigenous organic matter and its composition.

Spatial, temporal, and source variations of hydrocarbons in marine sediments from Baffin Bay, Eastern Canadian Arctic

The Canadian Arctic, including marine areas of Nunavut, in Canada's eastern Arctic, potentially contains large under□sea oil and natural gas reservoirs. Crude oils are complex mixtures of thousands of organic compounds, including alkanes (paraffins), cycloalkanes, polycyclic aromatic hydrocarbons (PAHs), and inorganic elements present as part of these compounds, including sulfur, vanadium, uranium, copper, and nickel (AMAP, 2007). PAHs in particular are an emerging chemical class of concern in some Arctic regions. Concentrations of PAHs in fish and invertebrates from the Barents and Norwegian seas were found to have increased 10 to 30-fold over the past 25 years (De Laender et al., 2011). The chemical structures and profiles (the relative concentrations of compounds) of hydrocarbons, including PAHs, provide useful biomarkers to infer hydrocarbon sources (Peters et al., 2007; Yunker et al., 2011).

Analysis of 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. In this study, we present preliminary results of hydrocarbon concentrations in three benthic invertebrate species (*Gorgoncephelus arcticus, Psilaster andromeda* & *Ctenodiscus crispatus*) collected from northern Baffin Bay during the 2013 CCGS *Amundsen* cruise. The data presented is the first baseline record of hydrocarbon concentrations in Baffin Bay biota in advance of offshore exploration and increased shipping activities.

Twenty years of air-water gas exchange observations for pesticides in the western Arctic Ocean

The arctic has been contaminated by legacy organochlorine pesticides (OCPs) and currently used pesticides (CUPs) through atmospheric transport and oceanic currents. Although CUPs are less persistent than OCPs, they are still detected in the arctic air, water and biota. The fate of these pesticides were studied by looking at water and air samples from sub-arctic and arctic regions between 1993-2013. Understanding the processes and current state of air-surface exchange is important in order to assess human and environmental exposure, evaluate the effectiveness of International Protocols and in turn provide OCPS: chlordanes, dieldrin and toxaphene and CUPs: dacthal, endosulfans, chlorothalonil, chlorpyrifos and trifluralin.

The delivery of contaminants to the Arctic food web: why sea ice matters

For decades sea ice has been perceived almost exclusively as a physical barrier for the airborne delivery of organic contaminants to the Arctic Ocean, and the presence of ice cover has been a deterrent to the flux between the seawater and air (Hargrave et al., 1997). Based on α-HCH as a process tracer, we postulate that first-year sea ice plays a profound role in the delivery of organic contaminants to Arctic food webs, increasing the exposure to biota through 1) high contaminant concentrations in the brine fraction of the sea ice itself (Pućko et al., 2010), 2) higher concentration of contaminants in the underlying seawater during early stages of ice formation (Pućko et al., 2013), and 3) the entry of atmospherically-deposited contaminants into surface waters mediated by melt ponds (Pućko et al., 2012). Because the efficacy of the above mentioned processes strongly depends on the ice type (first-year ice (FYI) versus multi-year ice (MYI)), the widespread transition from MYI to FYI in the Arctic Ocean is likewise widely altering the flux of contaminants to surface ocean. Specifically, MYI presents a weak brine engine (low content of salts in the brine fraction) and transient, relatively fresh melt ponds that refreeze in winter. In contrast, first-year ice forms widespread melt ponds containing more brine, and the water in these ponds enters the ocean as the ice rots and disappears annually toward the end of summer.

IRIS 1 – western and central high Arctic

Regional Impact Assessment: The Integrated Regional Impact Study (IRIS) framework was adopted by ArcticNet to provide regional-scale, accessible and comprehensive knowledge encompassing impacts of climate change and modernization (e.g. transition from country foods to store-bought foods). The IRIS 1 Regional Impact Assessment is the second of four IRIS reports to be released by ArcticNet. IRIS 1 covers the Inuvialuit Settlement Region (ISR) and the Kitikmeot region of Nunavut. This project has its beginnings in 2010 when the IRIS 1 leader (Gary Stern) and coordinator (Ashley Gaden) first started to put a steering committee together.

AACA: As IRIS 1 leader, Gary Stern was asked by AMAP to become involved in a co-leadership position with the USA and Russia in producing a regional impact assessment for the Barents/Chukchi/Beaufort (BBC) seas region and adjacent countries. This particular assessment will fall under the umbrella of the Adaptation Actions for a Changing Arctic (AACA) project led by AMAP. Peter Outridge was brought on as another Canadian co-chair to the project, and Ashley Gaden was asked to help also in her position as IRIS 1 coordinator.

ACTIVITIES

Transport and transformation of mercury across the ocean-sea ice-atmosphere (OSA) interface

- January-March 2014 & 2015: Mesocosm-scale experiment at the Sea-ice Environmental Research Facility (SERF).
- March-June 2014: Field study at Cambridge Bay on bromine and mercury chemistry in snow and sea ice.

- April-May 2014: Field study at Disko Bay, Greenland, on mercury methylation in various seawater micro-environments.
- June 2014-January 2015: Data analysis and interpretation (ongoing).

Hg isotope ratios in arctic environments

- Seawater samples and sediment cores were collected during previous ArcticNet expeditions (2012 and 2013) on board the CCGS *Amundsen* in the Canadian Arctic Archipelago (CAA) for Hg isotope ratio measurements. Seawater was either pre-concentrated on board (2013) or shipped back to the lab and processed there (2012).
- Sediment cores were sectioned on board (2013), frozen and transported back to the laboratory.
- In addition to Hg isotope ratio measurements, concentrations of total Hg (sediment, seawater) and MMHg (sediments) were determined. While the concentration measurements for Hg total were completed in 2013, MMHg measurements were conducted in 2014 and Hg isotope ratios measurements for sediment cores were also completed in 2014.

Distant drivers or local signals: Where do mercury trends in western Arctic belugas originate?

- Analysis of a total of 379 beluga tissues for total Hg, stable isotopes, and supporting parameters.
- Data analysis, manuscript preparation, submission, and publication.

Linking the carbon and mercury cycles in the Beaufort Sea using a seasonal, one-dimensional water column model

- We continued efforts to refine model performance regarding seasonal changes in methylmercury (MeHg, including mono- and dimethylmercury) formation and degradation in the water column and its uptake by lower trophic level organisms (ie phytoplankton and zooplankton) by trying to incorporate new findings from other ArcticNet mercury projects by Pućko et al. (2014) and Baya et al. (2015). These efforts will continue in 2015-2016.
- We developed several climate change scenarios based on previous work by Lavoie et al. (2010) in order to explore the potential impacts of climate change (principally change in ice cover, light regime, nutrient supply and timing of production blooms) on mercury speciation and fate in the water column.

The composition ($\delta^{13}C$, $\Delta^{14}C$ and lignins) of organic matter transported by rivers to Hudson Bay

- Collection of particulate and dissolved samples from 17 Hudson Bay rivers.
- Determination of total particulate and dissolved organic carbon for these rivers.
- Determination of lignin phenol compositions and concentrations on samples collected from these rivers.
- Development of MSc thesis (Godin, 2015) outlining the findings.

Spatial, temporal, and source variations of hydrocarbons in marine sediments from Baffin Bay, Eastern Canadian Arctic

- Analysis of hydrocarbons in sediment cores collected from the Baffin Bay during ArcticNet 2008 and 2009 cruises aboard the CCGS *Amundsen*.
- Data analysis, manuscript preparation, submission, and publication.

Analysis of Polycyclic Aromatic Hydrocarbons in benthic invertebrates from Baffin Bay

- A total of 9 samples of 3 different species of sea stars (collected from the Baffin Bay during the 2013 ArcticNet cruise on the CCGS *Amundsen*) were analyzed for 16 parent PAH concentrations and supplementary parameters.
- Preliminary data analysis was performed and a poster was presented at the ArcticNet annual meeting in Ottawa in December 2014.

Twenty years of air-water gas exchange observations for pesticides in the western Arctic Ocean

- During 2014, air, water, suspended particles and sediment samples were collected from the *Amundsen* during Legs 1 and 2. These samples will be analyzed for pesticides (legacy and current use), perfluorinated compounds, flame retardants and polycyclic aromatic compounds.

The delivery of contaminants to the Arctic food web: why sea ice matters

- April 2014-March 2015: Analysis of results, preparation and publication of the manuscript.

IRIS 1 – western and central high Arctic

- Regional Impact Assessment: Since the completion of the 2nd draft of the IRIS 1 Regional Impact Assessment in December 2013, external reviewers (scientists and government experts) along with IRIS 1 Steering Committee and Kitikmeot sub-committee members were asked to review individual chapters of the assessment. All chapters, with the exception of the Inuit Health Survey chapter (with 7-year old, well-analyzed data) and the climate chapter (which was not yet in a state to be reviewed), were reviewed following pre-determined guidelines (completed May 2014). Comments were sent back to the authors for revisions towards final drafts of their chapters. NEMO (oceanographic projections) output was also received from David Barber's group at U of M for incorporation into the assessment (May 2014); these were also given to select authors for their use. Steering committee meetings occurred on April 2, 2014 (teleconference) and December 10, 2014 (in-person at the Arctic Change 2014 conference) to update committee members on progress and receive feedback on the process and content of the regional impact assessment.
- Science to Policy document: The IRIS 1 leader and coordinator started discussions on how to develop the Science-to-Policy document that would complement and highlight the findings of the larger regional impact assessment. After consultation with policy experts at DFO, and with no funding to conduct a writing workshop with the IRIS 1 steering committee (e.g. IRIS 4's approach), it was decided, with consultation from the IRIS 1 steering committees, that the

IRIS 1 coordinator would write a first draft of the Synthesis and Recommendations article (completed July 21, 2014), which could then be edited by the IRIS 1 Steering Committee and Kitikmeot sub-committee (completed October 2014). Inuit language translators were sought and contacted for four languages in the ISR/Kitikmeot region (Inuinnaqtun, Inuktitut, and the Siglitun and Uummarmiut dialects of Inuvialuktun). However, two of these translators need to see the document before they can provide quotes for services.

- AACA: Peter, Gary and Ashley participated in weekly to bi-weekly teleconferences throughout 2014, assisting with concerns such as boundary issues, providing a list of Canadian representatives for a socio-economic online survey, editing the assessment's outline, and nominating authors for the assessment. Ashley attended a scenarios workshop in Vienna (May 2014), and Peter chaired a writers workshop held in conjunction with the Arctic Change Conference in Ottawa (December 2014).

RESULTS

Transport and transformation of mercury across the ocean-sea ice-atmosphere (OSA) interface

The SERF experiment confirmed that most Hg in newly formed sea ice is in the particulate form and is always enriched in the surface layer (Figure 1). Particulate Hg concentrations ranged from 61 to 437 ng g^{-1} within newly formed, nilas ice (<10 cm thick), and represented on average ~73% of total Hg species.

Fieldwork at Cambridge Bay showed bromide and chloride behave conservatively throughout the entire sea-ice core. However, the ratio of bromide to chloride changed considerably in the overlying snowpack,

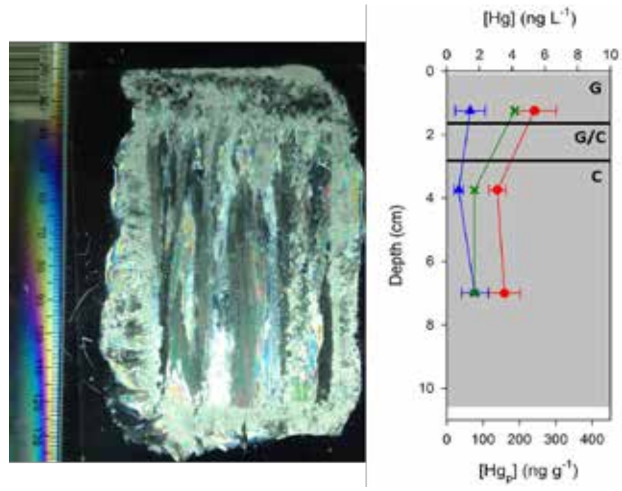

Figure 1. Distribution of mercury in experimental sea ice at SERF, showing the texture of sea ice (left) and the dominance of particulate mercury (right) (from Beattie et al., manuscript in preparation).

especially in the surface snow. This supports our previous postulation that bromine activation, the precursor for atmospheric mercury depletion events, occurs at the snow surface instead of on sea ice.

Seawater methylmercury mercury profiles obtained from the vast regions of Labrador Sea, Baffin Bay, North Water, and CAA showed a similar sub-surface peak as we reported earlier in the Beaufort Sea (Wang et al., 2012), although the ratio of methyl to total mercury was more variable.

Analysis of mercury samples from the micro-environment incubation experiments at Disko Bay, Greenland is ongoing.

Hg isotope ratios in arctic environments

For the first time, Hg isotope composition of seawater in the Canadian Arctic Archipelago is reported (Figure 2). Results showed negative mass dependent fractionation in the range from -2.85 to -1.10 ‰ for δ^{202}Hg, as well as slightly positive mass independent

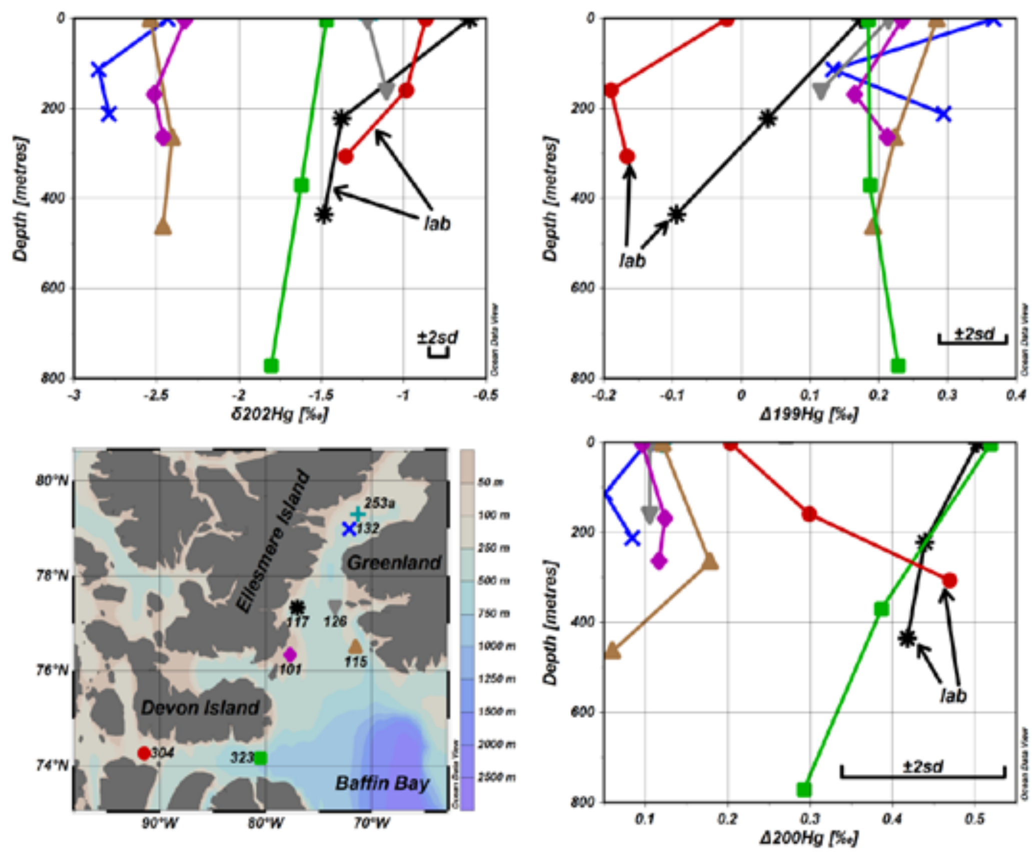

Figure 2. Seawater sampling sites and results for δ202Hg, δ199Hg and δ200Hg versus depth. Error bars represent the 2SD measured for the UM-Almadén reference solution. Results acquired from samples pre-concentrated in the laboratory are identified by the arrows.

fractionation of odd Hg isotopes. Positive mass independent fractionation of ^{200}Hg was also observed.

The results for mass dependent fractionation (δ^{202}Hg) from stations 101, 117, 132, 304 and 323 showed more positive values at the surface and more negative values in deeper layers of the water column. The results from stations 115 and 126 do not show higher δ^{202}Hg values in the surface samples. It is plausible that the origin of water in deeper layers from these stations is from the North Atlantic, carrying slightly different Hg isotope signature than surface waters. The evidence for this could be higher salinity in deeper layers compared to other stations, together with higher temperature.

All values for mass independent fractionation (δ^{199}Hg) fall in a relatively narrow range between 0.1-0.4 ‰. For most of the stations (101, 115, 126 and 323), no significant difference of δ^{199}Hg was observed with depth, at least within the method precision. In the case of station 117, δ^{199}Hg values decreased with sampling depth while at station 304 values are more positive at the top of the water column. At station 132, a minimum value was observed in the middle of the water column, whereas top and bottom samples showed comparable δ^{199}Hg values.

Significant isotopic anomalies (mass independent fractionation) for ^{200}Hg isotopes were observed at sites 101, 115, 117, 304 and 323. Average δ^{200}Hg values of surface samples from all sites (0.22 ‰) are almost identical to subsurface samples (0.23 ‰). Taking into account measurement uncertainties, there are no significant depth variations in δ^{200}Hg values, except for site 304. The sites could be grouped into two pools, one having δ^{200}Hg values between 0.3 and 0.5 ‰ and others between 0.1 and 0.2 ‰. Neither of these pools shows any specific spatial pattern or hydrographic correlation.

Distant drivers or local signals: Where do mercury trends in western Arctic belugas originate?

To investigate the relationship of muscle Hg and diet, δ^{15}N and δ^{13}C were examined over time within each size group, using years as an interaction variable. Hg concentrations in medium sized belugas showed significant relationships with δ^{15}N ($p = 0.001$; $r = 0.57$) and δ^{13}C ($p = 0.001$; $r = 0.56$) with 'years' as an interaction. Conversely, no significant relationships were observed in the large size group. To consider large-scale ecosystem shifts and decadal changes, the AO (Arctic Oscillation), PDO (Pacific Decadal Oscillation) and SIM (Sea-Ice Minimum) were used as indicators of regional change that could influence temporal trends in beluga Hg. The AO exhibited positive relationships for both the muscle (large size group) and liver (old group) Hg. Beluga muscle Hg had the most significant relationship with a three-year time lag to the AO ($p = 0.02$; $r = 0.55$). Among the lag series the best fit for liver Hg was a non-significant six-year time lag ($p = 0.13$; $r = 0.37$). Lastly the PDO showed a significant positive trend for an eight-year time lag for both Hg in muscle and liver (muscle: $p = 0.036$; $r = 0.51$; liver: $p = 0.001$; $r = 0.72$). A schematic diagram showing how climate variability might operate on the pathways, processes and interactions involving Hg and food webs is presented in Figure 3.

Linking the carbon and mercury cycles in the Beaufort Sea using a seasonal, one-dimensional water column model

Prior work with the model has shown that it produces concentrations of HgT of 60-200 $ng \cdot m^{-3}$ and MeHg of 5-95 $ng \cdot m^{-3}$, that are similar to those measured in the Beaufort Sea by Wang et al. (2012); 220±90 $ng \cdot m^{-3}$ HgT, 40±30 $ng \cdot m^{-3}$ MeHg (Figure 4). Model-generated depth profiles for HgT were in agreement with field measured profiles that are not influenced by inputs from the Mackenzie River. The model was also is in agreement with field data that showed peak production of MeHg occurs below the surface polar mixed layer that extends to 40-50 m (Wang et al., 2012), however getting good temporal agreement between the model and measured depth profiles of MeHg remains problematic primarily due to the lack of seasonally-sensitive mercury methylation/ demethylation rates in the water column. The current model predicts a large annual fluctuation in MeHg concentrations in the water column that is not supported by the available data (Wang et al., 2012). The stable MeHg concentrations from mid-July thru November (averaged across the upper 120 m) are similar to measured levels (~ 30-50% of HgT), but the predicted rapid decline in MeHg through the winter (to <1% of HgT) is greater in magnitude than the limited data from this period would suggest. The nearly 10-fold annual fluctuation in the mercury content in biota (phytoplankton and zooplankton) currently predicted by the model is driven by the realistic seasonal changes in phytoplankton biomass and by over-predicted fluctuation in the bioaccumulative MeHg supply.

Results from simulations involving climate change scenarios were consistent with the types and direction of changes we would expect in the mercury cycle although we need to resolve the issues with methylation and demethylation rates before proceeding further. In general, the climate change scenarios resulted in i) earlier input of mercury to the surface waters from melting snow and ice due to

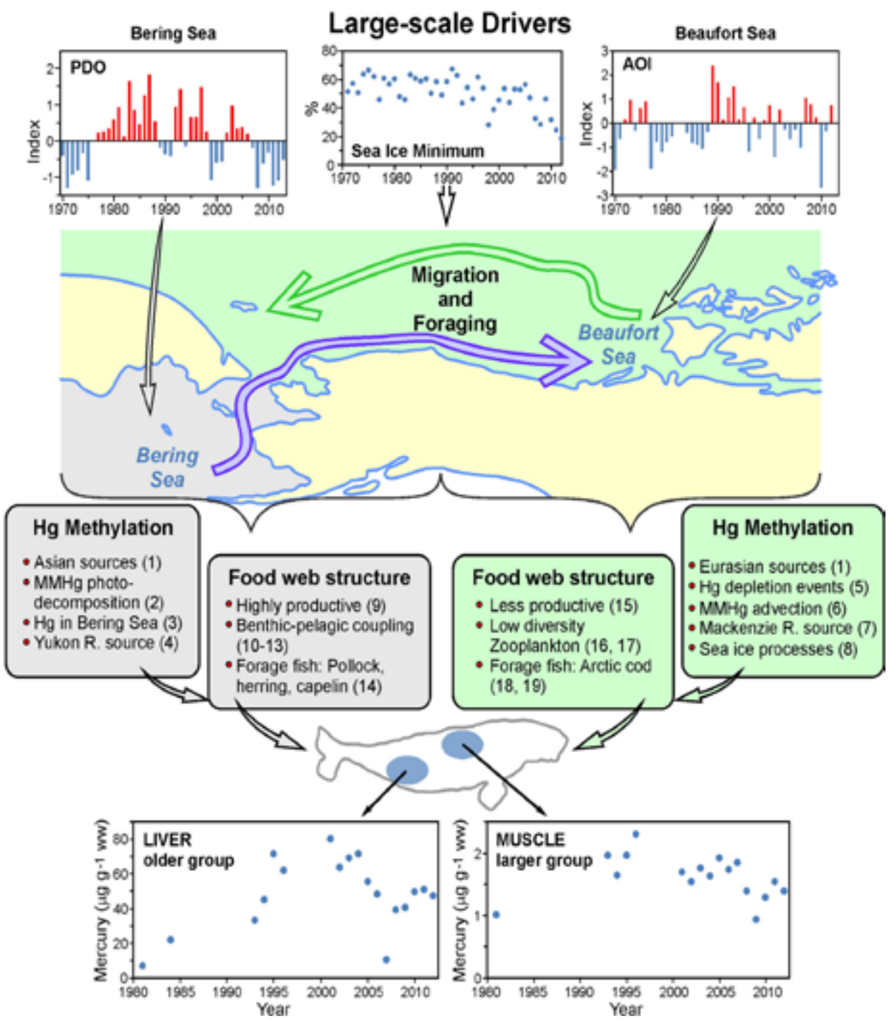

Figure 3. A schematic diagram showing how climate variability might operate on the pathways, processes and interactions involving Hg and food webs.

earlier ice breakup; ii) a modest decrease in mercury concentrations in surface waters during the longer open water period due to enhanced loss by evasion to the atmosphere and a modest increase in mercury transport to deeper waters with settling particles associated with an increase in primary production. The predicted increases in primary production (~10%) had little effect on particle associated transport below the 120 m domain of the model as most organic carbon is remineralized in the upper 100 m of the water column. The extent of mercury fluxes by evasion (as Hg0) and particle settling (primarily as MeHg) are sensitive to the speciation of mercury.

The composition ($\delta^{13}C$, $\Delta^{14}C$ and lignins) of organic matter transported by rivers to Hudson Bay

We have determined the annual flux of organic carbon (POC, DOC) from the 17 rivers in Hudson Bay by measuring the concentrations of these parameters and combining them with water-flow data (Figure 5). The data emphasize the dominance of inputs at the southwest corner of Hudson Bay, and in particular the importance of the Churchill/Nelson River sources to organic carbon supplied from land. The

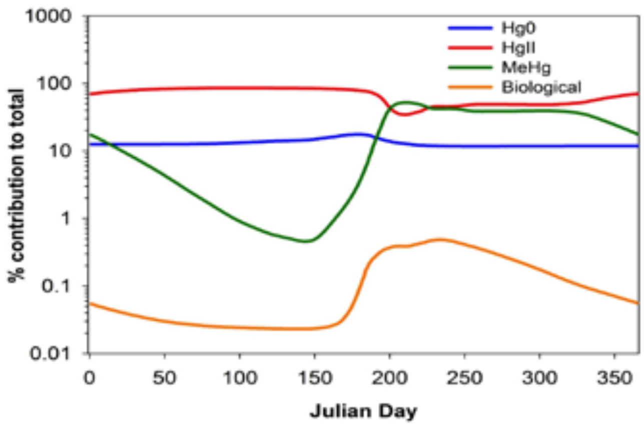

Figure 4. Percent contribution of each Hg species to total Hg in the model domain (120 m water column) over one year. The biological component includes all forms of detritus, ice algae, phytoplankton, and zooplankton.

lignin fluxes (not shown) look very similar to the flux distributions of the POC/DOC suggesting that biomarkers and terrigenous carbon will exhibit their strongest influence on sediments along the southern margin of the Bay. Most of the organic matter entering from rivers appears to be young in its Δ^{14}C age (<250 years), with the Churchill and Nestapoka Rivers providing exceptions (2500-3000 years). In terms of lignin composition (syryngyl (S), vanillyl (V), cinnamyl (C)), we find a range in characteristic indictors (S/V and C/V) that suggests both woody (gymnosperm) and non-woody (angiosperm) plants are the major contributing sources, but the relative strength of these two sources varies from south to north. Furthermore, decomposition indicators (e.g., acid aldehyde ratios) in lignin products tend to show that much of the terrigenous plant carbon entering rivers is relatively fresh (unweathered/metabolized) regardless of Δ^{14}C age.

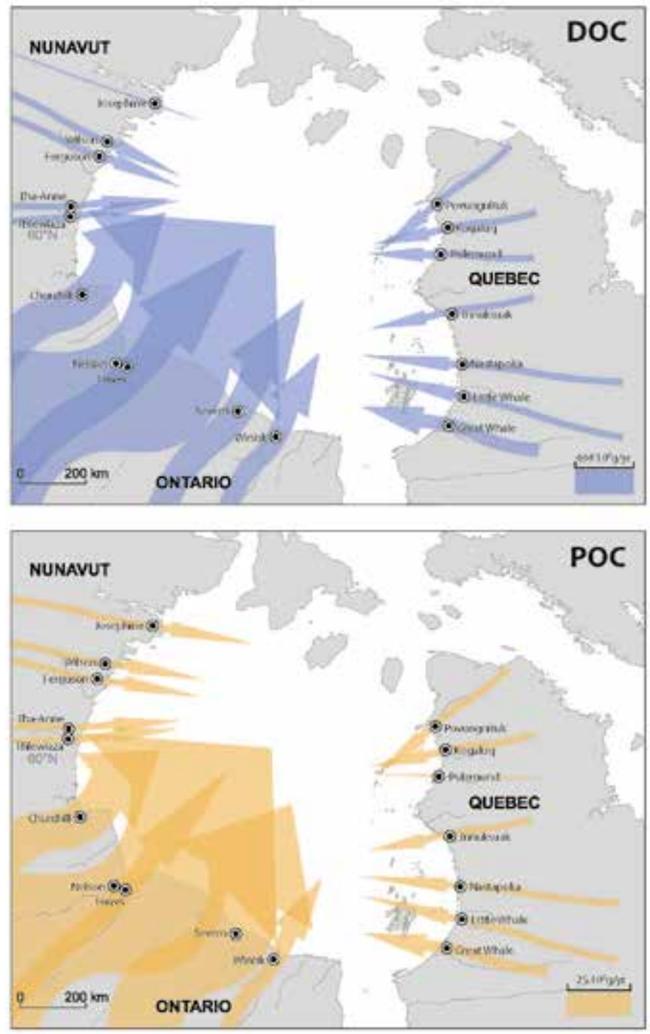

Figure 5. The annual flux of dissolved organic carbon (top) and particulate organic carbon (bottom) for 17 rivers entering Hudson Bay. Note the difference in scale between dissolved and particulate organic carbon panels.

Spatial, temporal, and source variations of hydrocarbons in marine sediments from Baffin Bay, Eastern Canadian Arctic

The highest concentrations of ΣPAHs in post-1900 sediments among the Baffin Bay cores were found at sites 111 and 108 within the NOW with concentrations of 2693.0 and 2111.1 ng g^{-1} dw, respectively (Figure 6). Measured concentrations exceeded the interim sediment quality guideline (ISQG) values in only one sample. The concentration of pyrene, a US EPA priority pollutant, exceeded the ISQG in surficial (3-3.5 cm) sediment at site 111 with a concentration of 188.0 ng g^{-1} dw compared to the ISQG value of 153 ng g^{-1} dw. Surface sediment concentrations of ΣPAH (parent and alkyl) reported across the Arctic

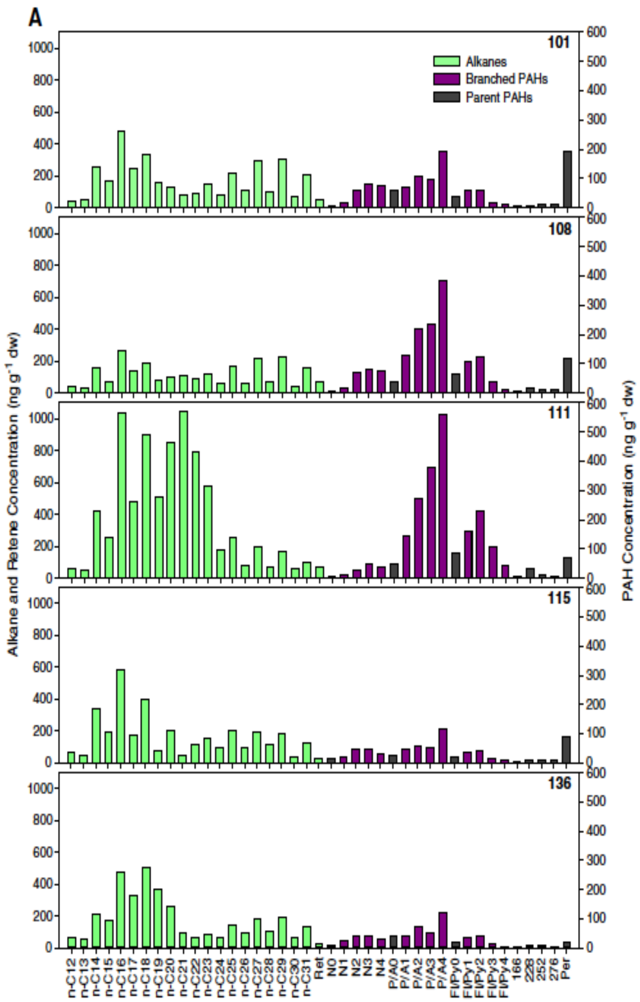

Figure 6. Surficial sediment (post-1900) concentrations of PAHs and alkanes predominantly from plant biomass (green bars), combustion (gray bars), and petrogenic (purple bars) sources from cores collected in Baffin Bay. From Foster et al. 2015. © 2014 Elsevier B.V. All rights reserved.

Ocean, which range from ~113 ng g^{-1} dw in the Makarov Basin to ~2959 ng g^{-1} dw in the Mackenzie Delta (Yunker et al., 2011), were comparable to those reported here for Baffin Bay.

Analysis of Polycyclic Aromatic Hydrocarbons in benthic invertebrates from Baffin Bay

PAH concentrations range from 34.5 to 107.3 ng/g dw. The threshold effect consensus found for PAHs is 1620 ng/g dw with probable effects at 22800 ng/g dw (Macdonald et al. 2000). Biota-to-Sediment-Accumulation Factors (BSAFs) for different species are shown in Figure 7.

Twenty years of air-water gas exchange observations for pesticides in the western Arctic Ocean

OCPs in air and water have declined in the Canadian Archipelago between 1999-2013 with few exceptions, although the water trends are harder to interpret because there are also spatial differences within the Canadian Archipelago for HCHs and chlordanes, where concentrations are higher in on the Pacific side compared to the Atlantic side. Levels of dieldrin, chlordane, toxaphene and heptachlor epoxide are approaching current detection limits in air and water, toxaphene in 2010-2011 was estimated at <5 pg/L and <5 pg/m^3 in water and air, respectively. Similar declines have been found in air for other OCPs at arctic monitoring sites (Kong et al., 2014; Hung et

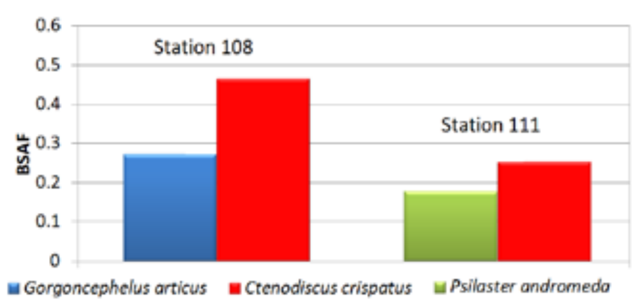

Figure 7. Biota-to-Sediment-Accumulation-Factors (BSAF) for ΣPAH16 are used to show the difference between the sediment-feeding C. crispatus and the predatory species G. arcticus and P. andromeda.

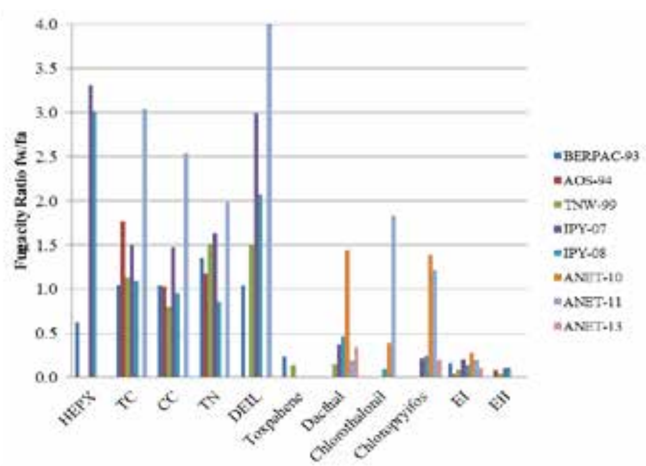

Figure 8. Fugacity ratio for OCPs and CUPs between 1993-2013, where 1.0 is equilibrium, <1.0 and >1.0 are deposition and volatilization, respectively. Fugacity ratios between 0.7-1.3 are not significantly different from 1.0.

al., 2010; CACAR III, 2013). Sampling volumes were increased in 2014 to achieve lower detection limits. CUPs, including endosulfans, chlorothalonil, chlorpyrifos and dacthal have been analyzed in air and water samples from the Canadian Archipelago by our group since 1999. Generally, CUPs are easily detected in arctic air and water with levels in water higher than the OCPs. Fugacity ratios for OCPs and CUPs between 1993 and 2013 are shown in Figure 8.

The delivery of contaminants to the Arctic food web: why sea ice matters

We have calculated meltwater equilibrium concentrations (C_{Eq}), meltwater near-equilibrium concentrations (C_{Neq}, actual concentrations that will be reached over the duration of pond coverage), and melt pond enrichment factors (MEFs), defined as CNeq divided by seawater concentration, for selected legacy OCPs and CUPs in the Beaufort Sea and Amundsen Gulf in May-July 2008. Predicted concentrations in melt pond water are relatively high for all of the CUPs compared to legacy OCPs, ranging from 27 +/- 28 pg·dm^{-3} for dacthal to 258 +/- 443 pg·dm^{-3} for chlorothalonil, and from 0.7 +/- 0.4 pg·dm^{-3} for trans-chlordane to 41 +/- 18 pg·dm^{-3} for dieldrin. The average duration of pond coverage in the Beaufort Sea of 35-58 days will allow for all of the OCPs and CUPs analyzed in this study to reach over 70% of equilibrium concentration with an exception of chlorothalonil which will approach only 10-20% of CEq due to its relatively low Henry's Law Constant. Modeling of air-water exchange dynamics assumes no supply of contaminants from the melting snow at the beginning of spring melt and no wet atmospheric deposition, again, a rather unrealistic scenario; however, the one we chose due to its conservative nature. In reality, we think that the melt ponds should reach the equilibrium partitioning with air considerably faster. Hypothetical contaminant pump functioning schematic using endosulfan I as an example is shown in Figure 9.

IRIS 1 – western and central high Arctic

Regional Impact Assessment: As of December 31, 2014, nine of the ten chapters had been revised for the third and final draft of the assessment. The climate chapter still needed some work, according to the lead authors. A local publisher worked with the IRIS 1 leader and coordinator to professionally format each of the chapters and will eventually compile them into a book for printing.

Science to Policy document: Once a few more quality photos are acquired, this piece will be ready to send to the publishers and be shown once more to the IRIS 1 Steering Committee, Kitikmeot sub-committee, and other choice reviewers.

AACA: It was determined that the main contribution of the Canadian co-chairs and IRIS 1 coordinator would be with respect to deliverables from the IRIS 1 project. In particular, contributions were offered to three of the BBC assessment chapters: Chapter 2 (stakeholder perspectives), Chapter 3 (environmental settings), and Chapter 4 (Impacts).

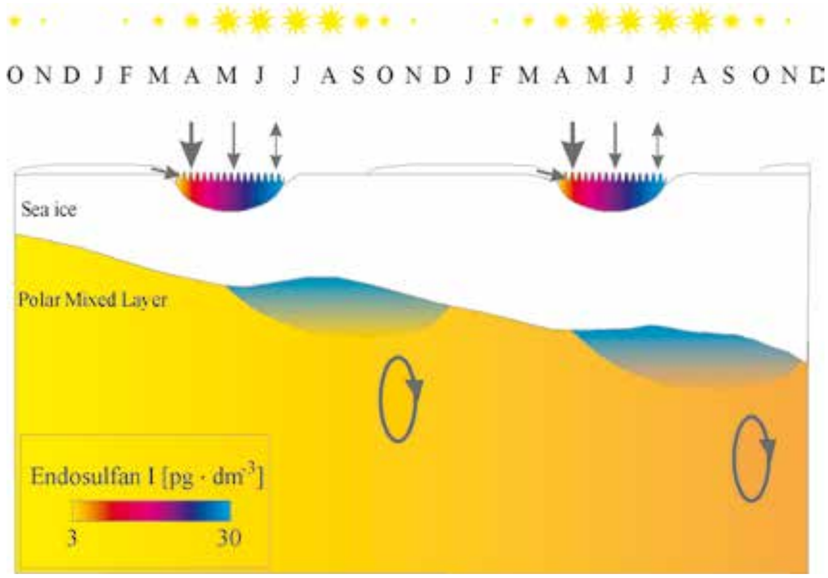

Figure 9. Hypothetical contaminant pump functioning schematic using endosulfan I as an example; colors denote endosulfan I concentrations in melt ponds and seawater. From Pucko et a., 2015.

DISCUSSION

Transport and transformation of mercury across the ocean-sea ice-atmosphere (OSA) interface

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 mercury in the Arctic marine ecosystem. One critical knowledge gap remaining is the process responsible for the production of methylmercury in subsurface seawater and sea ice. This will be our main research focus in 2015.

Hg isotope ratios in arctic environments

The average δ^{202}Hg values for the surface samples is -1.87 ± 0.63 ‰, which is within the expectations from values derived for riverine input (1 to -3 ‰), atmospheric deposition (-0.02 to -1.48 ‰) and snow melting (-1.35 ‰). Since evasion of Hg(0) would result in enrichment of heavier isotopes and consequently in more positive δ^{202}Hg values, our speculation is that removal of Hg(II) by particle settling to the sediment will enrich lighter isotopes in seawater to counterbalance this process. The average δ^{202}Hg values in top sediment layers from CAA (-0.76 ± 0.14 ‰, unpublished results).

Taking into account the narrow range of mass independent fractionation and considering that most samples did not show differences with depth, it was concluded that depth-related processes, which may alter δ^{199}Hg values, are not present or not detectable.

Currently, mechanisms that could cause mass independent fractionation of even isotopes are unknown. Neither current theoretical models nor laboratory experiments were able to explain or generate mass independent fractionation of even isotopes. However, the phenomenon has been described in several studies, and was so far mainly observed in precipitation. This study is the second report (after Štrok et al., 2014) of the presence of significant even mass isotope signatures in seawater. Chen et al. (2012) suggested a conceptual model, where ^{200}Hg fractionation occurs in the tropopause layer of the atmosphere during oxidation of Hg(0) to Hg(II) by ozone or hydroxyl and halogen radicals under intense sunlight irradiation. If this was correct and oxidation of Hg(0) is the only mechanism, responsible for even mass independent fractionation, then only Hg subjected to specific atmospheric conditions would show even mass independent fractionation and the magnitude of $\delta^{200}Hg$ fractionation would be proportional to the amount of Hg that underwent atmospheric transformation as described by Chen et al. (2012). If this concept holds, the measurement of $\delta^{200}Hg$ anomalies would be a powerful tracer to distinguish between Hg entering from the atmosphere by dry and wet deposition and Hg originating from other sources.

Distant drivers or local signals: Where do mercury trends in western Arctic belugas originate?

The PDO and AO are associated with ocean changes that impact both food webs and Hg methylation processes; with the PDO having a more significant influence in the Bering Sea and the AO in the Beaufort Sea. Irrespective of the PDO and AO, Hg processes across the oceans are influenced by different factors. For example, atmospheric sources of Hg to the Bering Sea are largely derived from Asia (AMAP, 2011). Significant inputs of Hg to the ocean and sediments (and subsequently the food web) in the Bering Sea include terrestrially derived Hg from the Yukon River (Day et al., 2012) as well as Hg arriving from the North Pacific to the Bering (Fox et al., 2014).

Linking the carbon and mercury cycles in the Beaufort Sea using a seasonal, one-dimensional water column model

Results from the model for HgT and MeHg in seawater are generally in good agreement with measured values collected in previous years (Wang et al., 2012). The model is consistent with recent literature (Cossa et al., 2009; Sunderland et al., 2009; Wang et al., 2012) that suggests that MeHg production and concentrations in seawater are tightly linked to processes in the carbon cycle throughout the year and thus indirectly associated with sea-ice, ligth regimes and nutrient supply. Climate change scenarios suggest an earlier breakup of sea ice, longer open water season, and increased frequency of upwelling may increase the amount of nutrients available to primary producers (Lavoie et al., 2010). Losses from the upper water column by evasion and particle-associated transport to greater depths, as well as bioaccumulation by plankton are sensitive to the balance between the formation of the various mercury species. While we believe the model performs adequately in describing conversions between Hg0 and HgII in the water column, the model does not yet adequately describe the formation and degradation of MeHg in relation to the seasonal changes in organic carbon production and remineralization.

The most important next step in developing the model remains with efforts to improve the MeHg component of the model by moving to a mechanistic kinetics-driven approach that is sensitive to seasonal changes in organic carbon production and remineralization. Currently, there is only one study that reports in situ kinetics in Arctic marine waters (Lehnherr et al., 2011) but it is limited to the late fall after peak periods of algal production and organic carbon remineralization. Measuring methylation/demethylation rates during upcoming field campaigns should be a priority, with special focus during the spring/summer phytoplankton bloom and subsequent period of elevated organic carbon remineralization. Other aspects of the model to improve likely include mercury speciation and exchange processes at the air/ice/water interface.

The composition (δ^{13}C, Δ^{14}C and lignins) of organic matter transported by rivers to Hudson Bay

The supply mechanism for the organic carbon carried by Hudson Bay rivers clearly involves surface soils in the active layer, where permafrost is present, and for the most part incorporates recently-produced plant litter that is decomposing in the surface soil reservoir. The old organic material (2500+ years) found in the Nestapoka and Churchill rivers is interesting because this matter appears fresh in its lignin composition. We infer that old matter is being released, either by bank erosion or permafrost degradation, but that processes of decay have been slowed down or stopped because the organic matter has been preserved in the frozen state until recently. The evidence for this can be found in the contradiction between acid aldehyde composition (low ratios) set against relatively high age (2500 years). Clearly, this observation is of great significance and worthy of further work, as it implies that these particular markers may be developed into an incisive method to detect permafrost thaw and subsequent release of old, archived matter. Once released, the ancient organic matter is open to degradation on the way to re-burial in Hudson Bay sediments, and would thus provide a feedback supplying ancient carbon to the inorganic carbon pool, either within Hudson Bay waters or to the atmosphere (e.g., see Vonk et al., 2012). The metabolism of this old carbon, therefore, has implications for the global CO_2 cycle and for bottom-water pH in Hudson Bay.

A second feature of the data that has large implications is the gradient from south to north in the composition of lignins carried by Hudson Bay rivers. This intriguing pattern was earlier inferred from sediment cores collected in Hudson Bay (Kuzyk et al., 2008), but at that time there was no direct evidence from the composition of organic matter transported by rivers. In particular, we have found that southern rivers favour lignins associated with gymnosperms (woody plants, boreal forest) and northern rivers favour lignin compounds associated with angiosperms (tundra). Clearly, this gradient potentially offers a second large-scale indicator of climate change manifest by the migration northward of permafrost thaw. Thawing would permit an alteration in the function of the active layer, deepening it and altering liquid water movement and supply, and would likely be accompanied by shifts in predominant vegetation type from tundra toward shrubs like willows. This latter shift could occur quickly (Hinzman et al., 2005), but a slower advance (century scale) of the tree line is also projected to occur (e.g., Fichefet et al., 2004). These varied processes would produce signals in the organic matter transported by rivers that can be understood and distinguished, provided that biomarker analyses and ^{14}C ages are monitored for the important organic pools (dissolved, colloidal and particulate) (e.g., see Guo et al., 2007).

Spatial, temporal, and source variations of hydrocarbons in marine sediments from Baffin Bay, Eastern Canadian Arctic

The sum of all measured hydrocarbon compounds in sediments represent a small fraction of the total organic carbon present in these sediments, between 0.02 and 0.19% depending on the site, yet their relative concentrations or chemical signatures are like fingerprints that indicate the source of organic carbon to the sites. The importance of both marine and terrigenous contributions to organic matter at all sites is also evident in the bimodal pattern of n-alkane concentrations in the chemical profiles. Odd C numbered higher n-alkanes (n-C25, n-C27, n-C29, and n-C31) associated with terrigenous, vascular plant sources of organic matter (Peters et al., 2007) comprised one mode, and lower n-alkanes (n-C15 to n-C21), characteristic of plankton (Bourbonniere and Meyers, 1996), comprised the other.

Analysis of Polycyclic Aromatic Hydrocarbons in benthic invertebrates from Baffin Bay

To quantify the extent of PAH exposure of the invertebrates, the biota-sediment accumulation factor (BSAF) is calculated to determine PAH uptake. This is calculated from the ratio between the biota PAH values analysed and the sediment values from Foster et al. (2015). From the two stations that we have multiple samples, *Ctenodiscus crispatus* has a higher ratio than the other two species BSAF = *Cb/Cs* where *Cb* and *Cs* are the ΣPAH16 concentrations in the biota and sediment samples, respectively, collected from the same location.

Twenty years of air-water gas exchange observations for pesticides in the western Arctic Ocean

From the water and air concentration and the temperature dependent Henry's Law constants, the net air-water gas exchange direction and magnitude can be estimated. Understanding the role of air-water exchange and the strength of this process in providing these chemicals to the base of the marine food web is vitally important, particularly if diminished sea-ice cover in a warmer arctic is likely to exacerbate the transfer from air to water for some chemicals.

Generally, the legacy OCPs in air and water are at equilibrium or volatilising from the water into the air, thus the Arctic Ocean is a secondary source of OCPs to the atmosphere. Generally, the CUPs are undergoing deposition with a few excursions to equilibrium. CUPs are more easily metabolized than OCPs and there are ongoing primary emissions of CUPs so the Arctic Ocean continues be to sink for these compounds. A study in 2010 in the Bering-Chukchi seas and Beaufort Sea also found endosulfan was depositing, chlorpyrifos was close to equilibrium or depositing and dacthal was at equilibrium or volatilizing (Zhong et al., 2011).

The delivery of contaminants to the Arctic food web: why sea ice matters

The process of atmospheric loading of contaminants to surface meltwater and subsequent drainage to the Arctic Ocean can be described as a 'pump' that transfers contaminants from the atmosphere to an ice-covered ocean via pond meltwater. To determine the significance of this contaminant input route to the Arctic Ocean, we calculated the total quantity of various CUPs that would be delivered to the surface seawater of the Beaufort Sea in 2008 via melt pond leakage into the ocean compared to the standing stock of CUPs held in the Mixed Layer of the Beaufort Sea. The total amount of CUPs discharged to the Beaufort Sea with surface meltwater drainage in 2008 was calculated to be 6 kg for dacthal, 16 kg for chlorpyrifos, 6 kg for endosulfan I, and 54 kg for chlorothalonil. The hypothetical contaminant 'pump' could, therefore, deliver annually about 2% of dacthal, 4% of chlorpyrifos, 10% of endosulfan I, and 4% of chlorothalonil relative to the standing stock in the Polar Mixed Layer (40 m).

IRIS 1 – western and central high Arctic

Although the Regional Impact Assessment was not ready for publication by the end of the 2014, it is clear that with the continued support of the IRIS 1 Steering Committee, Kitikmeot sub-committee, authors, reviewers and other supporters, the assessment will be well on its way to publication in 2015 in time for the ArcticNet site visit. The climate chapter was received on January 22, 2015 and every effort is being made to expedite its readiness for publication.

With respect to the BCB assessment, the deadline for a first draft of all chapters is set for March 2015. With the wrap-up of the writers workshop in December 2014, no deliverables from the Canadian co-chairs had been contributed as of December 31, 2014.

CONCLUSION

Transport and transformation of mercury across the ocean-sea ice-atmosphere (OSA) interface

We were able to show major processes controlling mercury distribution in sea ice, and discovered new hotspots for mercury methylation. Modeling efforts are needed to project how a changing sea ice will affect mercury cycling in the Arctic.

Hg isotope ratios in arctic environments

We were successful in developing a methodology allowing the determination of Hg isotope ratios in seawater.

The technology detected measurable difference in mas dependent fractionation of Hg isotopes (^{202}Hg). Observed depth profiles are explained by Hg(II) reduction and evasion of Hg(0) to the atmosphere in surface waters and Hg(I)) adsorption to settling particles.

Taking into account currently known values of $\delta^{200}Hg$ anomalies in precipitation, from Greenland snow and assuming no anomalies in Hg from riverine and erosion input, a simple mixing model can be employed for an initial source apportioning. Assuming constant $\delta^{200}Hg$ value of the precipitation in the CAA of around 1.2 ‰, observed seawater $\delta^{200}Hg$ values could indicate the magnitude of riverine and erosion Hg flux to the water table at specific station. Sites having $\delta^{200}Hg$ values between 0.3 and 0.5 ‰ would have approx. 50 % of total Hg input from riverine and erosion origin, whereas values between 0.1 and 0.2 ‰ would have approx. 80% riverine and erosion input of Hg.

Distant drivers or local signals: Where do mercury trends in western Arctic belugas originate?

In the case of the Beaufort Sea beluga population, and many other migratory Arctic species, one has to consider the life course that spans across oceans and outside of the Arctic. All of our observations in the Arctic during the past several decades have occurred during a time of large-scale change with sea-ice and permafrost/snow providing the clear manifestations since the early 1990s. In our first examination of leading climate variables in the Arctic, we have found plausible relationships between Hg in beluga and the PDO and to a lesser extent the SIM. These relationships imply that some of the variability in beluga Hg loads is associated with Bering Sea climate variability, and we need more complete data on winter foraging patterns and food webs to understand the processes and linkages between climate variables, diet and Hg concentrations in belugas caught in the Beaufort Sea. The lags between the observed beluga Hg concentrations and the climate drivers investigated here (5±3 years), if confirmed with longer time series, would be helpful because they provide predictability of future Hg concentrations.

Linking the carbon and mercury cycles in the Beaufort Sea using a seasonal, one-dimensional water column model

Results from the model for total- and methyl mercury in seawater are generally in good agreement with measured values collected in previous years, however the predicted seasonal variation in MeHg concentrations are likely greater than what actually occurs.

The model suggests that MeHg concentrations in seawater throughout the year are highly dependent on the carbon cycle and thus indirectly associated with sea-ice regimes, hence making the mercury cycle sensitive to climate change.

Preliminary climate change scenario modelling suggests there will be greater loss of mercury to the atmosphere by evasion and possibly a small increase in particle-associated transport of mercury to deeper waters due to increased primary production.

These predictions are sensitive to the balance between the formation of the various mercury species under varying conditions associated with season and depth.

The most important refinements to the model are efforts to develop (and calibrate) a mechanistic kinetics-driven approach to calculating methylation/demethylation that is sensitive to seasonal changes in organic carbon production and remineralization.

In situ measurements of methylation/demethylation rates during upcoming field campaigns should be a priority, with special focus during the spring/summer phytoplankton bloom and subsequent period of elevated organic carbon remineralization.

The composition ($\delta^{13}C$, $\Delta^{14}C$ and lignins) of organic matter transported by rivers to Hudson Bay

Given that we have collected only a single point in time for these rivers, we cannot say whether change is already manifested in our data as a consequence of permafrost thaw or vegetative shifts over the past, say, twenty years or so. But with these data we have provided a benchmark against which to evaluate future change. Additionally, the determination of the distribution of these biomarkers provides us with a far better basis to infer past conditions using dated sediment cores collected from within Hudson Bay.

Spatial, temporal, and source variations of hydrocarbons in marine sediments from Baffin Bay, Eastern Canadian Arctic

The data presented provide a baseline record of hydrocarbon concentrations and chemical profiles in northern Baffin Bay sediments. With so little known about hydrocarbons in northern Baffin Bay, the significance of these results is that they provide a preliminary characterization of the spatial variability in both present-day and historic sediments (pre-1900), and an indication of the relative importance of different natural sources (marine versus terrigenous). In general, concentrations and fluxes of hydrocarbons to sediments were higher within the polynya (101, 108, 111, 115, 136, and 138) than elsewhere (141, 205, 233, 301, and GBF). Whether this indicates a local source of hydrocarbons, particularly petrogenic PAHs, to the NOW or a different mechanism for sequestering hydrocarbons from the water column by suspended particulates and subsequent deposition to the sediments, remains unclear. However, the hydrocarbon biomarkers and chemical profiles in the sediments suggest the predominance of petrogenic, as opposed to combustion, PAHs at all sites included in this study.

Analysis of Polycyclic Aromatic Hydrocarbons in benthic invertebrates from Baffin Bay

The modified QuEChERS method in combination with silica gel chromatography has provided for a Quick, Easy, Cheap, Efficient, Rugged and Safe method to extract Polycyclic Aromatic Hydrocarbons (PAHs) from biological tissues. The highest concentrations of PAHs measured in benthic invertebrates were well below the levels generally giving rise to measurable physiological and ecological effects. *Gorgoncephelus arcticus* had the highest concentrations of benzo[a] pyrene giving rise to the highest TEQ (Toxic Equivalent) values. BSAF values are the highest for *Ctenodiscus crispatus* and reflect the ecological (mode of feeding) and physiological characteristics of individual species (PAH metabolism by *Gorgoncephelus arctics*/*Psilaster andromeda* but not *Ctenodiscus crispatus*).

Twenty years of air-water gas exchange observations for pesticides in the western Arctic Ocean

International regulations that have limited the usage of organochlorine pesticides have results in lower concentrations in arctic air and water. These lower levels will results in lower levels in arctic biota but there will be a lag time. Endosulfan has been recently added to the Stockholm Convention on persistent organic pollutants; it will be interesting in the coming years to track how the levels in arctic air and water respond to reduced primary emissions.

The delivery of contaminants to the Arctic food web: why sea ice matters

The ongoing transition from perennial to annual ice forms is changing the role of sea ice in contaminant pathways; we propose that for some chemicals this has meant a shift from inhibiting the transport of atmospheric contaminants into the surface ocean to facilitating such transport. FYI contains more brine and contaminants, and thus is much more efficient in the delivery of contaminants to the Arctic food web via exposures to ice-associated biota compared to the disappearing old ice. FYI experiences high growth rates at the beginning of its annual life cycle, while old ice growth rates are much slower due to the insulating effect of the existing ice and/or snow cover. With an increasing percent coverage of the Arctic by FYI relative to the old ice, a hypothetical contaminant pump will be turned on over vast areas of the Arctic Ocean with as of yet poorly understood consequences. Almost certainly, this sort of climate change will complicate the interpretation of contaminant trends measured in marine biota. Transition towards a FYI-dominated summer Arctic may, therefore, result in over 40% increase of efficacy of the melt pond hypothetical contaminant 'pump' due to complete melting of ice each year, and a greater volume of meltwater due to higher air temperatures and increased precipitation. In such a scenario, however, the importance of atmospheric deposition of organic contaminants to the surface meltwater will depend on the length of time meltwater will have to accumulate contaminants from the atmosphere before complete thawing takes place, again, a climate change parameter of significance.

IRIS 1 – western and central high Arctic

Leading up to the publication of the regional impact assessment, the next step with IRIS 1 is to strategize how to disseminate the assessment's results to the ISR and the Kitikmeot region. This topic was previously visited during the two steering committee meetings in 2014, and based off these early discussions it seems likely that the IRIS 1 leader and coordinator will engage IRC and NTI in forming an IRIS Communications Committee.

The BCB Canadian co-chairs and coordinator remain ready at the helm to continue participation in the AACA project.

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The composition ($\delta^{13}C$, $\Delta^{14}C$ and lignins) of organic matter transported by rivers to Hudson Bay

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IRIS 1 – western and central high Arctic

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MARINE BIOLOGICAL HOTSPOTS: ECOSYSTEM SERVICES AND SUSCEPTIBILITY TO CLIMATE CHANGE

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Modelling Benthic Biodiversity in Relation to Environmental Parameters in the Canadian Arctic
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Nutrient cycling in Arctic marine ecosystems
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Variabilité spatiale et temporelle des communautés bactérienne et phytoplanctonique dans les fjords subarctiques de la côte Est du Canada
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L'arctique : un environnement dynamique pour les nanoflagellés hétérotrophiques
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Impact du bioenrichissement engendré par les colonies d'oiseaux migrateurs (Fulmarus glacialis et Uria lomvia) sur les assemblages benthiques, détroit de Lancaster et Pond Inlet, Arctique canadien
Vincent Carrier, Masters Student (UNIS - The University Centre in Svalbard)
Biogeography of marine pico- and nanoeukaryotes around Svalbard Archipelago, Norway
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Tracing organic matter sources of Canadian Arctic benthic invertebrates with stable isotopes
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Comparative Transcriptomics of Five Arctic Microalgae Species Under Environmentally Relevant Growth Conditions
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ABSTRACT

Living, harvestable resources in the upper Arctic Ocean ultimately depend on the production of marine microalgae. Microalgal production also mitigates global warming by fixing the greenhouse gas CO_2 into biomass, of which a portion sinks to the seafloor. This process, called the 'biological CO_2 pump', supplies food to the benthic organisms living at the bottom. Ongoing alterations of the physical environment will have profound impacts on the growth conditions of primary producers, affecting the timing, productivity and spatial extent of biological hotspots (i.e. areas of elevated food web productivity against the low background typical of the Canadian Arctic). This project investigates how changes in the dynamics of sea-ice and glacial ice (icebergs and ice islands), water temperature, ocean circulation and wind forcing affect primary production in the upper water column and the benthic ecosystem underneath. Specific objectives are to 1) locate biological hotspots (and coldspots) of pelagic and benthic activity, 2) assess how they function and interact, and 3) assess how their productivity and biodiversity is likely to respond to further perturbations of the environment. To do so, we are and have been developing and implementing cutting-edge observational and experimental approaches that exploit remote sensing from space, autonomous underwater vehicles, as well as the sampling and laboratory facilities of the CCGS *Amundsen*. Our work is done in very close collaboration with several ArcticNet projects, collaborators and partners from government and the industry.

KEY MESSAGES

In order to shorten our report this year, we have divided key messages in two categories that pertain to 1) the results described in detail in the following sections and 2) other important work not described in detail (bullet points).

Key Messages (emanating from the results presented)

- First in situ evidence of change in the net biological productivity of high-latitude western Arctic seas.
- Net community production (NCP) shifted differently in two contrasted Canadian oceanographic settings.
- Seasonal nitrate consumption increased 1.6-fold between 2003–2004 and 2010–2011 in the stratified southeast Beaufort Sea whereas nitrate consumption in the once productive North Water Polynya declined by 65% and is now nearly on par with the oligotrophic coastal Beaufort Sea.
- Remote sensing analysis showed the bloom started earlier in 2009 and 2013 than in 1998 and 2001 in the North Water Polynya that is probably related to the inter-annual variability of the sea ice-retreat timing and the stabilization of the upper mixed layer.
- The length of the bloom period appears to be inversely correlated ($r^2 = 0.6$, $p < 0.001$; relation not showed) with the bloom start: an early spring bloom corresponds to greater bloom duration (and vice versa).
- Since 2002, the relative abundance of diatoms tends to increase in the Beaufort Sea while the phytoplankton production, biomass and abundance stayed relatively constant during autumn.
- From 1999 to 2011 in northern Baffin Bay, phytoplankton production, biomass and abundance during autumn gradually decreased by 20, 3 and 10 times, respectively. The production and biomass of phytoplankton, which used to be dominated by large cells, are now dominated by small cells.
- Significant seasonal differences in phytoplankton structure and function were evidence for Labrador fjords, with highly productive ecosystem in summer but with low primary production, chl a biomass and abundance of large phytoplankton (>2 µm) in autumn.
- The seasonal variations in phytoplankton dynamics in Labrador fjords are mostly controlled by the strength of vertical stratification and daylength, which is strongly seasonal in these high-latitude fjords.
- Labrador fjords exhibit a low potential for vertical carbon export out of the euphotic zone (≤31% of total primary production), which suggests that phytoplankton there is mainly grazed by microzooplankton in surface waters.
- Primary production and Chl a biomass do not significantly differ across Labrador fjords, but sclerochronological analysis of the shells of Portlandia arctica (a bivalve) suggests differences in the sinking export of food to the benthos.
- New molecular tools we developed to describe the distribution of different groups of Heterotrophic marine flagellate taxa. We found that changing ice cover and mixing regimes are expected to impact these ecologically-significant grazers in the Canadian Arctic.

Other key messages

- For the Canadian Arctic, we defined 6 benthic community types based on biomass-weighted taxonomic composition. Their distribution was significantly, but moderately, associated with large-scale (100-1000 km) environmental gradients in bottom depth, physical water properties and meso-scale environmental gradients defined by substrate type (hard vs. soft) and sediment organic carbon content.

- Depth and salinity were the main environmental predictors of macrobenthos patterns at the regional scale, while sediment grain size was a good environmental predictor at a sub-regional scale on the shelf (< 200 m).
- Surface sediment pigments and organic carbon are not good predictors of macrobenthos patterns at the regional scale.
- Sea-ice algae are a determinant carbon source for benthic communities in the Canadian Arctic.
- In Lancaster Sound and Pond Inlet, chl a concentration, sediment type and depth seem to exert a greater influence on spatial epibenthic faunal patterns than the organic matter provided by colonial seabirds.
- Results on fatty acid trophic markers of the neutral lipids show that the microalgal blooms exported from the euphotic zone to the seafloor are the main food source for *Bathyarca glacialis*, even in deep environments.
- In the case of potential deficiency in essential fatty acids, *Bathyarca glacialis* shows a remarkable response in its diet by the synthesizing non-methylene interrupted fatty acids.
- Through the in situ TS analysis, we evidenced the depth segregation of polar cod sizes and their association with warmer waters
- Our biomass estimates showed that adult polar cod densities in Amundsen Gulf compare with that of rich areas such as the Barents Sea.
- We bring support to the assumption by Geoffroy et al. (2011) that dense aggregations do not form until the ice cover is consolidated.
- We showed that polar cod distributes continuously along slopes and that the Amundsen Gulf would be the source for aggregations that form in winter.

OBJECTIVES

Long-term Objectives

- Determine where pelagic and benthic hotspots (or coldspots) of productivity and diversity occur, how they function and are likely to shift in the future.
- Adapt remote-sensing techniques for the estimation of phytoplankton biomass and suspended matter in the particular environment of the Arctic Ocean, with the aim of better characterizing the spatio-temporal variability of primary production at different spatial scales.
- Elucidate the oceanic, cryospheric and atmospheric drivers of microalgal primary production and microbial diversity in surface waters.
- Relate key indices of primary production to the biomass and diversity of consumers in the lower pelagic and benthic food web.
- Assemble decadal time-series to deconvolute the effect of different forcing mechanisms (inter-annual variability, climate oscillations, climate change) on productivity and biodiversity.
- Develop and/or implement cutting-edge approaches to augment the spatial and temporal coverage and resolution of observations on the productivity and biodiversity of the lower food web.

Specific objectives for 2014

- Detect and quantify decadal changes in the biological productivity of northern Baffin Bay and the southeast Beaufort Sea, based on the magnitude and ratios of seasonal nutrient drawdown. Relate these changes to transformations of the physical environment.

- Generate synoptic assessments of variability and change in productivity from remotely sensed properties of the sea surface in Baffin Bay (using satellites). Validate these estimates at select locations using the nutrient drawdown method (above).
- Characterize, for the first time, the marine ecosystems of Labrador fjords and evaluate the environmental factors that affect phytoplankton dynamics there.
- Develop molecular tools to identify heterotrophic marine flagellates (HF) and track their distribution over time and space.
- Assess the extent of the disturbances affecting high latitudes benthic fauna at decadal and centennial time scales by using bivalve sclerochronology.
- Verify the premises of the polar cod aggregation mechanism by determining its distribution and habitat characteristics prior to the formation of winter aggregations.
- Generate time-series of beluga occurrence from their calls and assess the underwater noise levels for a range of conditions.

INTRODUCTION

Drastic reductions in the extent, thickness and seasonal persistence of sea ice (Kwok and Rothrock, 2009; Markus et al., 2009; Maslanik et al., 2011) augment the penetration of sunlight into the Arctic Ocean, setting the stage for a rise in primary production and the yield of harvestable resources (Arrigo et al., 2011; Rysgaard et al., 1999). The realization of this potential also depends on nutrient availability, which was shown to explain large-scale differences in productivity across the Arctic (Tremblay and Gagnon, 2009). While recent increases in the freshwater content of the upper ocean increases vertical stratification and reduce the upward flux of nutrients in some sectors (Li et al., 2009; Rabe et al., 2011), the increasing strength and frequency of strong wind events may also increase nutrient supply and productivity through upwelling, vertical mixing and eddy generation in specific areas (Pickart et al., 2013; Rainville and Woodgate, 2009; Tremblay et al., 2011). Whether primary production undergoes enduring upward or downward shifts in a given seasonally ice-free region thus depends on a combination of factors, including light availability and altered nutrient loading resulting from changes in the freshwater balance (stratification), horizontal transport and atmospheric forcing of the upper ocean (Tremblay and Gagnon, 2009).

To our knowledge, there are no published time series of in situ measurements available to establish change in primary production across specific sectors of the High Arctic and validate the estimates obtained by remote sensing. Using the database we assembled during ArcticNet (since 2004) and in previous projects (since 1997), we started to assess decadal productivity shifts through changes in nutrient inventories. To this end, a comparison of nutrient inventories between winter (when the surface ocean has been recharged with nutrients) and the end of the growth period can provide time-integrated estimates of productivity (Codispoti et al., 2013; Matrai and Apollonio, 2013; Tremblay et al., 2002; Tremblay et al., 2008). The cumulative depletion of phosphate and total inorganic nitrogen over a growing season reflects net community production (NCP), which drives net changes in biomass and living resource yield. Moreover, changes in the relative drawdown of different nutrients provide coarse indications of change in the contribution of nutritious diatoms to NCP, since these organisms have distinct requirements for silicon and phosphorus. Diatoms need silicon to synthesize their frustules (Brzezinski, 1985) and have a high requirement for phosphorus, which has been linked to their investment in cellular components that support fast-growth (Deutsch and Weber, 2012; Geider and La Roche, 2002).

In this year’s report we document changes in the magnitude and ratios of nutrient drawdown in the High Canadian Arctic, comparing two regions with historically contrasted mixing regimes and exposure to the advection of Atlantic vs. Pacific-derived waters. The Canadian Beaufort Shelf in the southeast Beaufort Sea (BS) is categorized as an oligotrophic system due to its strong vertical stratification (Brugel et al., 2009; Carmack et al., 2004) and influenced by Pacific-derived waters supplied via the Beaufort Gyre and the Alaskan coastal current. Northern Baffin Bay (BB), the site of the secular North Water Polynya, has been a seasonally well mixed and among the most productive marine area of the Arctic circle (Barber et al., 2001; Klein et al., 2002) through which Pacific-derived water from the High Arctic exits in the west and Atlantic-derived water moves north in the east (Tremblay et al., 2002).

The trends observed from remote-sensing 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 obtained when CCGS *Amundsen* visits the High Canadian Arctic during late summer and autumn. This detailed data provides a necessary perspective on the environmental factors causing the change in a given area. We also report on the results of our first comprehensive investigation of primary production in three Labrador fjords and relate those to the growth of the benthic bivalve *Portlandia arctica* using shell sclerochronology or organisms obtained in glaciated and unglaciated fjords. This unique approach allows to assess the disturbances affecting high latitudes benthic fauna and to reconstruct environmentally-driven changes in growth conditions at the decadal and centennial time scales.

Finally, bacterivorous, single-celled marine eukaryotes, often referred to as heterotrophic nanoflagelates (HNF), are a principle agent of bacterial loss in Arctic waters (Vaque ́et al., 2008), where microbial food webs are active for much of the year (Rokkan Iversen and Seuthe, 2011). HNF are important for the maintenance of the ecosystem in the winter and contribute to transfer carbon to the higher food web during summer. As with many small single-celled taxa, however, a lack of diagnostic morphological features makes identification of HNF groups challenging. Here we developed and implemented molecular-based techniques to characterize the distribution of these important grazers in the High Canadian Arctic.

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 (29) and book chapters (7).
- Wide dissemination of scientific results via talk (31) and poster (32) presentations during national/international conference: ASLO Aquatic Sciences meeting (Portland, Oregon, USA), CMOS meeting (Rimouski, Canada), Arctic Change 2014 (Montréal, Canada), ASLO winter meeting (Granada, Spain), Statistical Society of Canada Annual Meeting (Toronto, Canada), Ocean Optics XXI (Portland, Maine, USA), General Meeting of Québec-Océan (Rivière-du-Loup, Canada), National Program on Remote Sensing (Paris, France), Arctic Biodiversity Congress (Trondheim, Norway), Annual Colloquium at the Centre for Northern Studies (Québec, Canada), Physiomar Conference (La Serena, Chile), Ocean Sciences Meeting (Honolulu, USA), Gordon Research Conference on Polar Marine Science (Barga, Italy).
- Participation to workshops: ART Workshop (Brest, France), 4th Ocean Color Workshop (Boulogne-sur-mer, France), Hydrology workshop (Venice, Italy), Ouranos Workshop (Québec City, Canada), Workshop on Underwater Noise and its Impacts on Marine and Coastal Biodiversity (London, UK).
- Participation of three NIs in the first stages of the AACA (Adaptation Actions for a Changing

Arctic) process, including participation to a planning meeting. Tremblay co-leads the 'living resources' section and leads the 'marine ecosystem' chapter.

- Invited poster presentation (C. Lovejoy) at the Arctic Biodiversity Congress (Trondheim, Norway).
- Bouchard-Marmen won best talk award at the World Conference on Marine Biodiversity (Qingdao, China).
- Virginie Roy has been involved in the re-assessment of original ecologically and biologically significant areas (EBSAs) in the Beaufort Sea Large Ocean Management Area.

2. HQP training

- Five PhD students successfully defended their thesis (S. Nahavandian, C. Sévigny, V. Roy, M. Ardyna, S. Ben Mustapha).
- Two MSc students handed in their dissertation and graduated (K. Chalut, G. Deslongchamps).
- New MSc students Fannie Tremblay and Isabelle Courchesne started last September.

3. Field work in the Canadian Arctic (IRISes 1,2 & 4)

- Joint ArcticNet/Netcare/GreenEdge on the *Amundsen* (J. Charette, M. Blais, C. Lovejoy, N. Joli, M. Gosselin, M. Parenteau, K. Campbell, A. Chagnon-Lafortune, N. Friscourt, C. Grant, C. Nozais and L. Paquette, J. Laliberté, Z. Amorena, J.-É. Tremblay, I. Courchesne, J. Gagnon, J.-S. Côté, P. Coupel, N. Schiffrine).
- Collaboration with the wintering expedition of the ship *Vagabond* in Qiqiktarjuak, to collect baseline ecosystem data in western Baffin Bay (winter/spring 2014).
- Participation in the IOS expedition aboard the *Louis St. Laurent* to the Canada Basin in October 2014 (D. Honda, R. Edgars).
- Planning meetings and preparation for the GreenEdge project in western Baffin Bay (planned for March-June 2015).
- J.-A. Dorval went to Cambridge Bay (September 14-25) to collect samples.
- B. Gaillard has been part of a sampling survey in Nuuk.

4. Field work in the context of international collaborations

- Invited participation the Subice expedition of the US icebreaker *Healy* (May-June 2014) to investigate the under-ice phytoplankton blooms in the Chukchi Sea.
- Invited participation to two expeditions of the RV *Helmer Hansen* (May and August 2014) to collect bloom and post-bloom data in the Atlantic water inflow near Snear Svalbard (Norwegian funded project Carbon Bridge).
- Participation to an experimental mesocosm deployment in Svalbard to investigate the impact of a simulated oil spill on ice-algal ecology (led by Akvaplan Niva in Norway with private funding from the International Association of Oil and Gas Producers–OGP).
- Preparation of the German-led TRANSSIZ expedition on board *Polarstern* (planned for May-June 2015).

5. Laboratory work, instrumentation, analysis

- Julien Laliberté (Msc student) evaluated the performance of the satellite-based approach of Bélanger et al. (2013) to estimate incident solar irradiance used in their primary production model using a large in situ data set gather since 1998. The method is being compared to the NASA algorithm.
- Dr. Clémence Goyens (Post-doctoral fellow) performed a match-up exercise between satellite (MODIS-Aqua) and in situ measurements of the so-called "remote sensing reflectance".

- Christian Marchese (PhD student) improved the method to extract the phytoplankton phenology from remote sensing data and begin the analysis of the physical forcing to better understand the year-to-year variability of phytoplankton in the North Water polynya.
- Samples form the numerous 2014 expeditions have been analyzed in several laboratories

6. Others activities

- Participation to the Helicopter Ditching course of several members of the hotspot group (Falck Safety Services, Dartmouth, N.S.).
- Planning and redaction of the successful Arc3Bio proposal for ArcticNet phase 4.
- Site visit for the BaySys project in Winnipeg (award granted).

RESULTS

1. Shifts in biological productivity inferred from nutrient drawdown and remote sensing analysis in the southern Beaufort Sea and Baffin Bay (NI: J.-É. Tremblay, S. Bélanger, HPQ: C. Marchese, M. Bergeron)

From 2003 to 2011 in the Southeast Beaufort Sea, the mean salinity of the upper ocean (an index of freshwater dilution of nutrients) and the depth of the halocline did not change appreciably throughout the time series (Figure 1a-b). However, the median depth of the nitracline increased by 3.6 m yr^{-1} while median nitrate drawdown rose by +13.4 mmol m^{-2} yr^{-1} (Figure 1c-d). The mean position of the subsurface chlorophyll maximum (SCM) incidentally deepened by 2.2 m yr^{-1} in the interval ($p < 0.001$, $r^2 = 0.09$, Fig 1c). Despite the increase in nitrate consumption, no change was observed in the silicate:nitrate and nitrate:phosphate drawdown ratios, implying that diatoms drove the change in net productivity (not shown but see Table 2 in Bergeron and Tremblay 2014).

Between 1997 and 2011 in Northern Baffin Bay (North Water at 76.3°N), the depths of the halocline and nitracline stayed nearly constant, but surface salinity decreased by 0.22 yr^{-1} (Figure 2a-c). This effect remained significant ($p = 0.027$) when the combined effect of sampling year and sampling date was considered (ANOVA; not shown). The decreasing salinity trend is consistent with the freshening of Canada Basin source waters for the west (Yamamoto-Kawai et al., 2009b) and implies an increase in vertical stratification. Nitrate drawdown decreased at the mean rate of 26.3 mmol m^{-2} yr^{-1}, with a maximum of 802 mmol m^{-2} in 1998 and a minimum of 214 mmol m^{-2} in 2009 (Figure 2d). The decreasing trend was more pronounced in western BB (-28.6 mmol m^{-2} yr^{-1}, $r^2 = 0.39$, $p = 0.018$,) than in eastern BB (-19.9 mmol m^{-2} yr^{-1}, $r^2 = 0.28$, $p = 0.002$).

Seasonal time series of satellite derived chlorophyll-a values from 1998 to 2013 are shown in Figure 3 for northern Baffin Bay (North Water). This analysis clear shows a repetitive pattern with a single bloom that is rarely followed by a secondary bloom. When it occurs (e.g. 1997 and 2009), this secondary bloom is much less pronounced than the first one. The magnitude of the spring bloom (i.e. maximum chlorophyll-a reached) is highly variable between years. The onset of the bloom generally occurs between the second half of April and the first half of May (Figure 3; dashed green line), but also exhibited considerable variability. As an extreme example, the bloom in 2009 began one month earlier than in 1999. The timing of bloom peak (Figure 3; red dashed line) also varied, with a difference of ca. one month between the record years of 1998 and 2012.

Temporal trends for the date of bloom onset, its duration and its magnitude (or peak chlorophyll-a concentration) are shown in Figure 4. The bloom's onset occurs significantly earlier with time, which is presumably caused by changes in the time of sea-ice retreat and stabilization of the upper mixed layer.

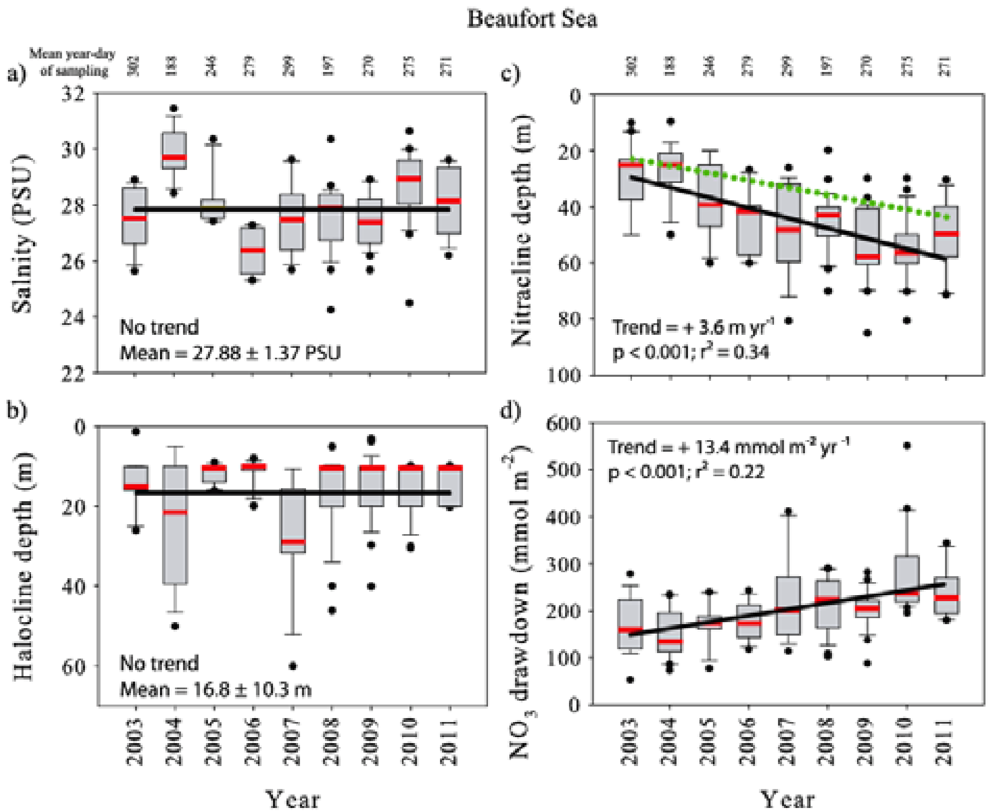

Figure 1. Box plots of the (a) weighted mean salinity in the first 50 m of the water column, (b) vertical position of the halocline, (c) nitracline depth, and (d) seasonal nitrate (NO_3^-) drawdown for the Beaufort Sea. Each box represents 50% of the observations, and the red mark gives the median value. Whiskers provide ranges for the upper and lower quartiles, and circles indicate extreme values. The black linear regression lines (trends) were fitted using all individual data points (not plotted). The green line in Figure 1c gives the trend in the mean vertical position of the subsurface chlorophyll maximum (SCM) ($r^2 = 0.09$; $p < 0.001$). Note the different vertical scales. The mean year-day of sampling is noted on the upper axis. Figure from Bergeron and Tremblay 2014. © 2014, John Wiley and Sons. © 2014. American Geophysical Union. All Rights Reserved.

Basically, a sudden loss of ice cover may facilitate the penetration of light into the water column creating, together with the presence of sufficient nutrients in the euphotic zone, the right conditions for the start of the bloom. By contrast, the duration of the bloom did not exhibit a clear positive trend despite considerable inter-annual variability. There is however and inverse correlation (r^2= 0.6, $p < 0.001$; not shown) between duration and onset - an early spring bloom corresponds to a prolonged duration. The peak chlorophyll-a concentration attained during the bloom shows a clear decrease over time, consistent with the drastic decline in annual productivity reported by Bélanger et al. (2013).

2. Changes in phytoplankton production, biomass and composition based on direct observations made during late summer and autumn (PI: M. Gosselin, M. Poulin, Y. Gratton and J.-É. Tremblay; HPQ : M. Blais, S. Lessard)

In the southeastern Beaufort Sea, phytoplankton production, biomass and abundance during late

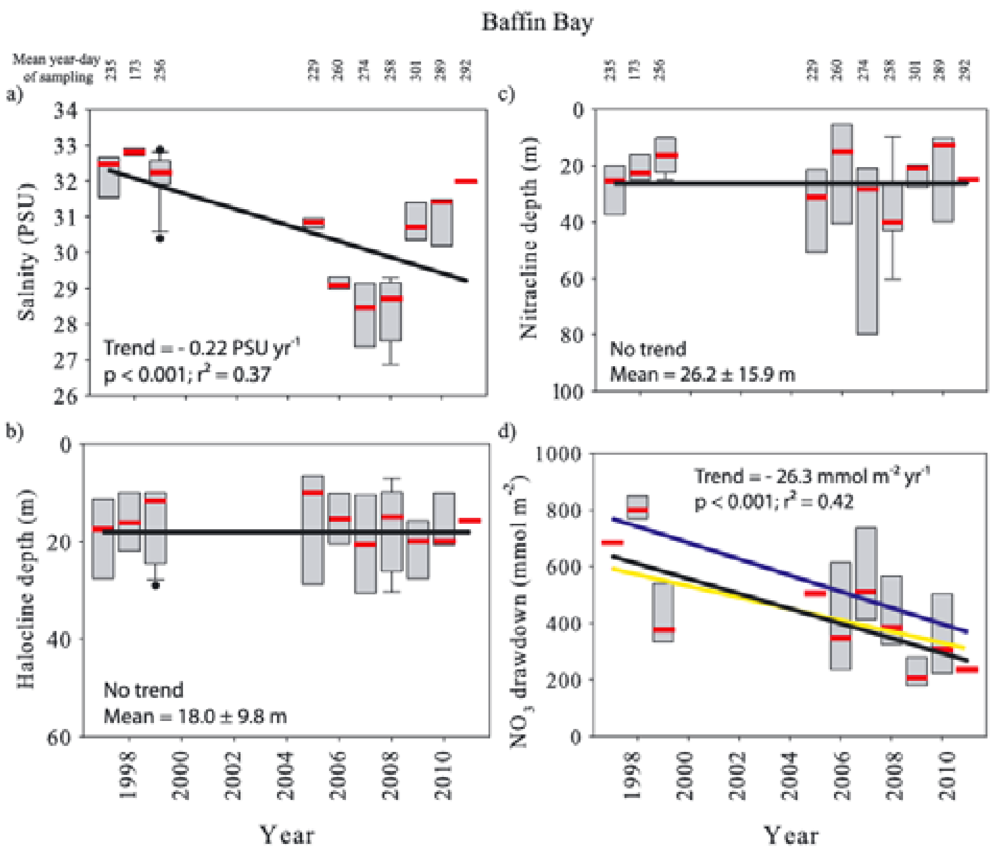

Figure 2. Box plots of the (a) weighted mean salinity in the first 50 m of the water column, (b) vertical position of the halocline, (c) nitracline depth, and (d) seasonal nitrate (NO_3^-) drawdown for Baffin Bay. Linear regression lines (trends) are given in black for the whole section, in blue for eastern Baffin Bay (-19.9 mmol m^{-2} yr^{-1}, $r^2 = 0.28$, $p = 0.002$) and in yellow for western Baffin Bay (yellow; -28.6 mmol m^{-2} yr^{-1}, $r^2 = 0.39$, $p = 0.018$). The mean year-day of sampling is noted on the upper axis. See Figure 1 for an explanation of the box plots. From Bergeron and Tremblay (2014). © 2014, John Wiley and Sons. ©2014. American Geophysical Union. All Rights Reserved.

summer/early autumn stayed relatively constant over the years, except for 2010 when the three variables showed positive anomalies corresponding to a dominance by large cells (>5 µm), mostly centric diatoms (Figs. 5a, 6a, 7a). Otherwise production and biomass were systematically dominated by small cells (0.7-5 µm), mostly nanoflagellates. The anomalous year of 2010 notwithstanding, there was a significant increase in the abundance of diatoms over time. These trends contrast with those obtained for northern Baffin Bay at 76.3° N (1999 to 2011), where primary production gradually decreased by ca. 20-fold (from 717 mg C m^{-2} d^{-1} to 41 mg C m^{-2} d^{-1}; Figure 5a), phytoplankton biomass by 3-fold (from 76 to 26 mg chl a m^{-2}; Figure 5b) and total cell abundance by ca. 10-fold (from 1.4 to 4.3 x 10^6 cells L^{-1} in 1999–taken from Booth et al. 2002 but not shown here–to 0.25 x 10^6 cells L^{-1} in 2011; Figure 7c). Phytoplankton production and biomass, which used to be dominated by large cells, are now dominated by small cells. Diatoms were the most abundant cells in 1999, 2006 and 2007 but represented less than 10% of total cell abundance in 2011.

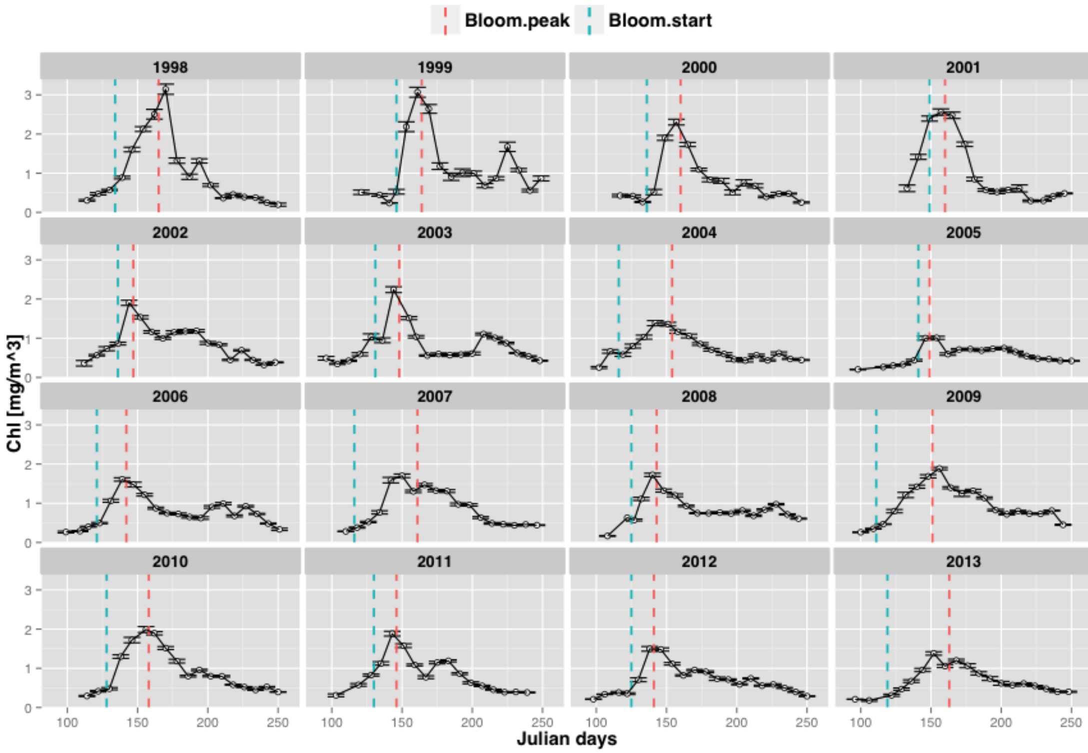

Figure 3. Seasonal time courses of chlorophyll-a (with standard deviation) in the North Water for the years 1998 to 2013, based on remote sensing. Vertical dashed lines indicate the timing of bloom start (green) and peak.

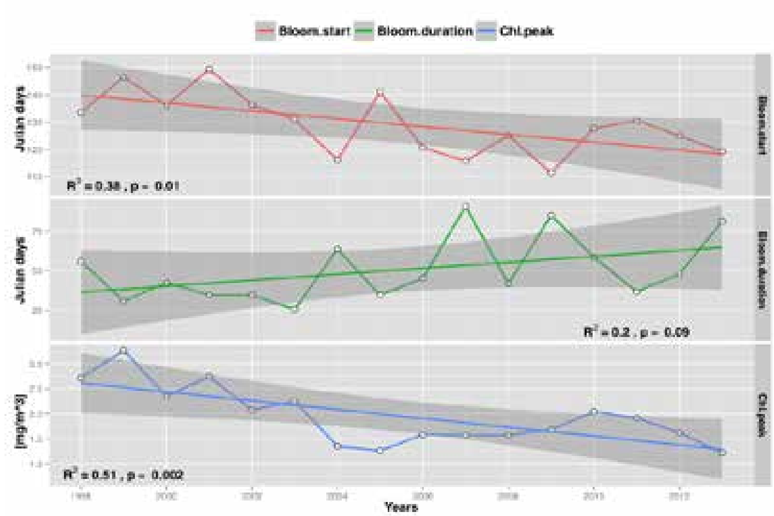

Figure 4. Inter-annual time series (data points) and trends (lines) of bloom start (red), bloom duration (green) and peak chlorophyll-a concentration (blue) in the North Water, based on remote sensing. Dark grey areas delineate the 95% confidence intervals on the trend lines.

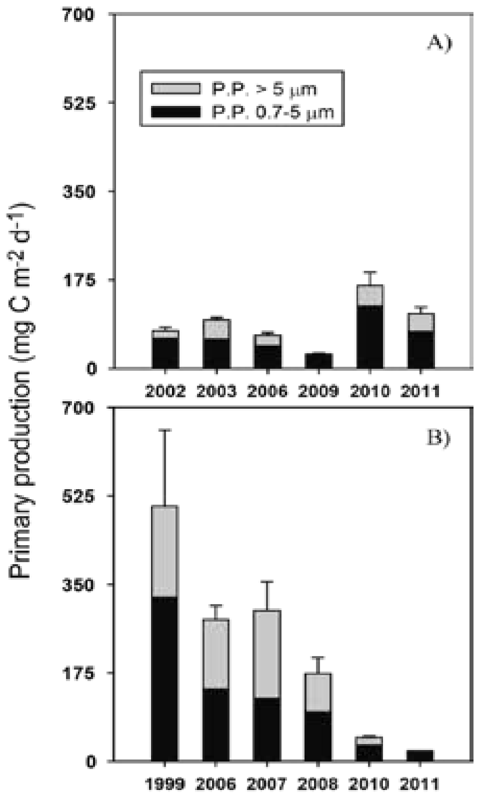

Figure 5. Interannual variation in the average rates (± 0.5 standard error) of primary production for small and large phytoplankton cells, considering all stations sampled in late summer/early autumn in A) the southeast Beaufort Sea and B) northern Baffin Bay at 76.3° N. Data were integrated over the euphotic zone (down to 0.2% surface irradiance).

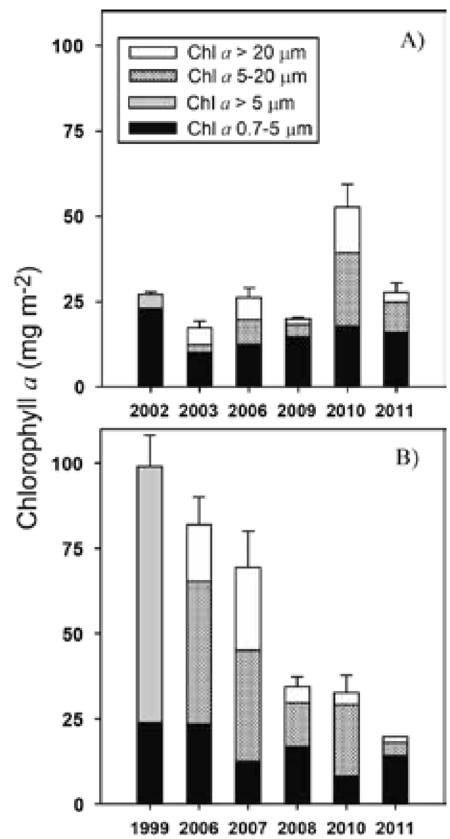

Figure 6. Interannual variation in the average standing stocks (± 0.5 standard error) of chlorophyll a in three size fractions, considering all stations sampled in late summer/early autumn in A) the southeast Beaufort Sea and B) northern Baffin Bay at 76.3° N. Data were integrated over the euphotic zone (down to 0.2% surface irradiance). Note that only 2 size fractions were measured in 1999 and 2002.

3. Seasonal variations of phytoplankton dynamics in Nunatsiavut fjords (Labrador, Canada) and their relationships with environmental conditions (NI: M. Gosselin, Y. Gratton, J.-É. Tremblay, HPQ: A. G. Simo Matchim, M. Blais)

We assessed phytoplankton dynamics and their environmental controls in four Labrador fjords (Nachvak, Saglek, Okak and Anaktalak) during summer 2007, early fall 2010 and late fall 2009, and described, for the first time, the seasonal and inter-annual variability of physical oceanographic conditions in these fjords (Figure 8).

On each sampling occasion, primary production and chlorophyll a (chl a) biomass were measured at seven optical depths, including the depth of the subsurface chl a maximum (SCM). Phytoplankton abundance, size structure and taxonomy were determined only for the SCM. Principal Component analysis and non-metric multidimensional scaling were used to analyze relationships between production, biomass and community composition in relation to environmental variables. We observed a marked seasonal variability, with significant differences in phytoplankton structure and function between summer and fall. Despite the latitudinal gradient and different local conditions,

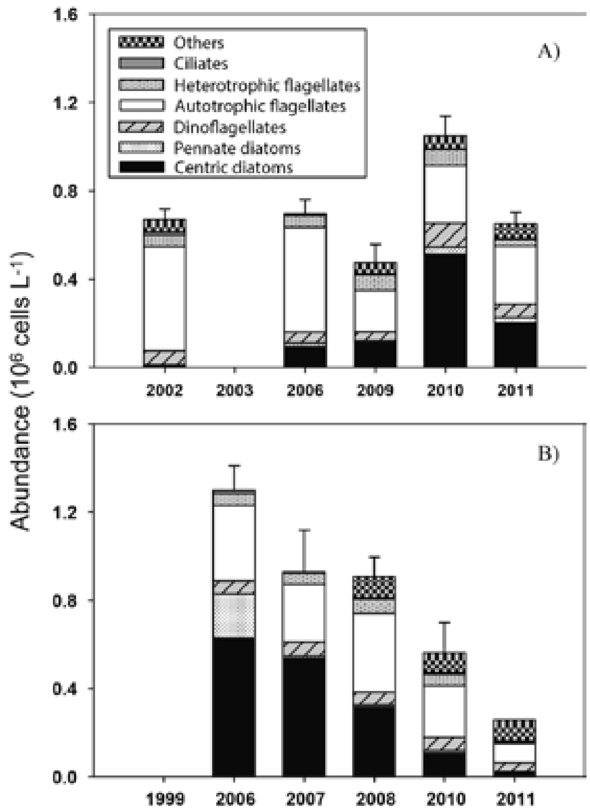

Figure 7. Interannual variation in the average abundance (± 0.5 standard error) of different groups of protists, considering all stations sampled in late summer/ early autumn in A) the southeast Beaufort Sea and B) northern Baffin Bay at 76.3° N. The autotrophic flagellate group includes chlorophyceae, chrysophyceae, dictyochophyceae, cryptophyceae, euglenophyceae, prasinophyceae, prymnesiophyceae, raphidophyceae and unidentified flagellates. The heterotrophic flagellate group comprises species such as Telonema sp., Leucocryptos marina and Meringosphaera mediterranea, along with choanoflagellates. Others include unidentified cells. Total protist abundance is not available for Baffin Bay in 1999. However, the abundance of the dominant centric diatom Chaetoceros socialis ranged from 1.4 to 4.3 x 10^6 cells L^{-1} at our sampling site in the euphotic zone (Booth et al., 2002).

primary production and chl a biomass did not differ significantly between fjords. The highest values of primary production (1730 mg C m^{-2} d^{-1}) and chl a biomass (96 mg chl a m^{-2}) were measured during summer and indicate that the four fjords are highly productive ecosystems. Summer protist communities exhibited a high abundance of nanophytoplankton (2-20 µm), whereas autumn communities were characterized by low primary production and chl a biomass, as well as relatively high abundances of picophytoplankton (<2 µm). Throughout the study, the small portion (≤31%) of primary production occurring in large cells (>5 µm) indicates a low potential for carbon export out of the euphotic zone. This observation suggests that microzooplankton grazing was the dominant pathway of carbon flow in these fjords. During summer, we observed a mixed assemblage of diatoms and flagellates, whereas autumn communities were largely dominated by flagellates. The seasonal variations in phytoplankton dynamics were mainly controlled by the strength of vertical stratification (i.e. difference in salinity between the surface and deeper waters; see Figure 8) and by the large differences in daylength imparted by the northerly location of these fjords.

4. Biogeography of heterotrophic flagellate populations indicates the presence of generalist and specialist taxa in the Arctic Ocean (NI: C. Lovejoy, HQP: M. Thaler)

Phylogenetic placement algorithms and the short reads generated by high throughput sequencing provided a means of identifying HNF (Heterotrophic nanoflagellates) from environmental samples and a tool for tracking HF distributions over time and space. This was the first pan-Arctic study examining species and ecotype level diversity in Cryomonadida, Telonemia, Picozoa, choanoflagellates and marine stramenopiles (Figure 9).

We re-analyzed new and previously published high throughput sequencing data from multiple studies in the Arctic Ocean, to identify broad patterns in the distribution of individual taxa. HF accounted for fewer than 2% to over half of the reads from the water column, and up to 60% of reads from ice, which was dominated by *Cryothecomonas*. In the water column, many HF phylotypes belonging to Telonemia, Picozoa, uncultured marine stramenopiles

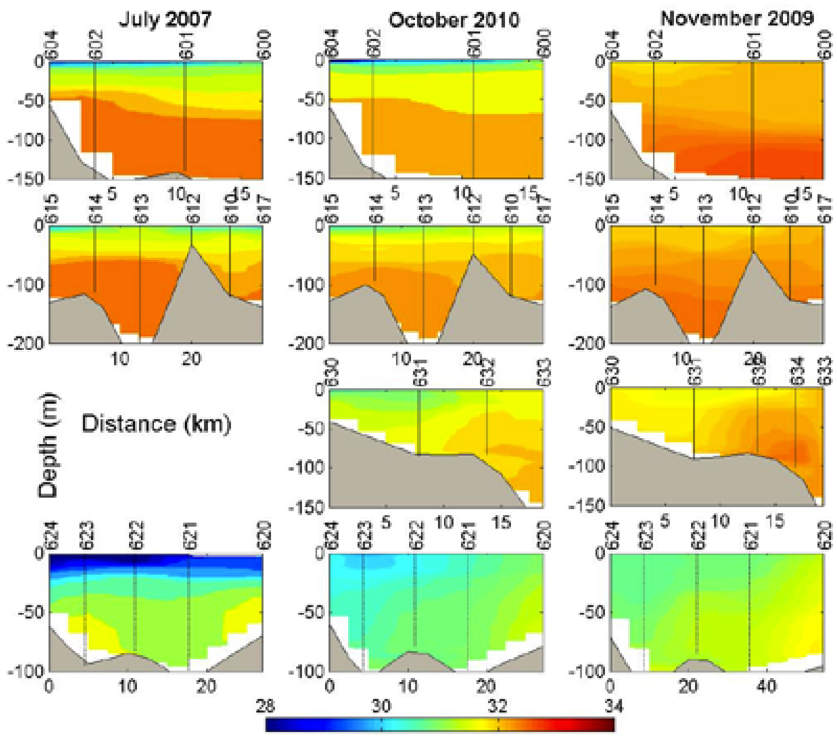

Figure 8. Salinity contours for four Labrador fjords. Each row of panels is from the same fjord, starting from the northernmost fjord (Nachvak) at the top and moving south to Saglek, Okak and then Anaktalak at the bottom. The columns are sorted by season, starting with July on the left (2007) and moving to October (2010) and November (2009). Vertical lines indicate the location of the sampling stations (numbers).

(MAST), and choanoflagellates were geographically widely distributed. However, for two groups in particular, Telonemia and *Cryothecomonas*, some species-level taxa showed more restricted distributions. For example, several phylotypes of Telonemia favoured open waters with lower nutrients such as the Canada Basin and offshore of the Mackenzie Shelf.

5. Using the bivalve Portlandia arctica as an indicator of environmental variations within glaciated and unglaciated fjords (Labrador, Canada) (NI: P. Archambault, C. Nozais, HPQ: K. Chalut)

Shells of the deposit feeder *Portlandia arctica* were collected in October 2010 within the subarctic fjords Nachvak (glaciated) (n=31) and Saglek (unglaciated) (n=30) (Northern Labrador), and growth layers were analyzed by sclerochronology. Estimated annual growth rates revealed a significant difference between the fjords ($F_{1,21} = 5.59$, $p = 0.028$) (Figure 10). Such disparity was potentially due to food inputs (phytodetritus), which appeared to be significantly higher within Saglek, despite similar levels of primary production in the fjords (see section 3 above). In addition, while standardized growth indices could be explained by various combinations of environmental factors at the local scale, they showed no clear temporal trend nor did they correlate with climate oscillations such as NAO on a regional level.

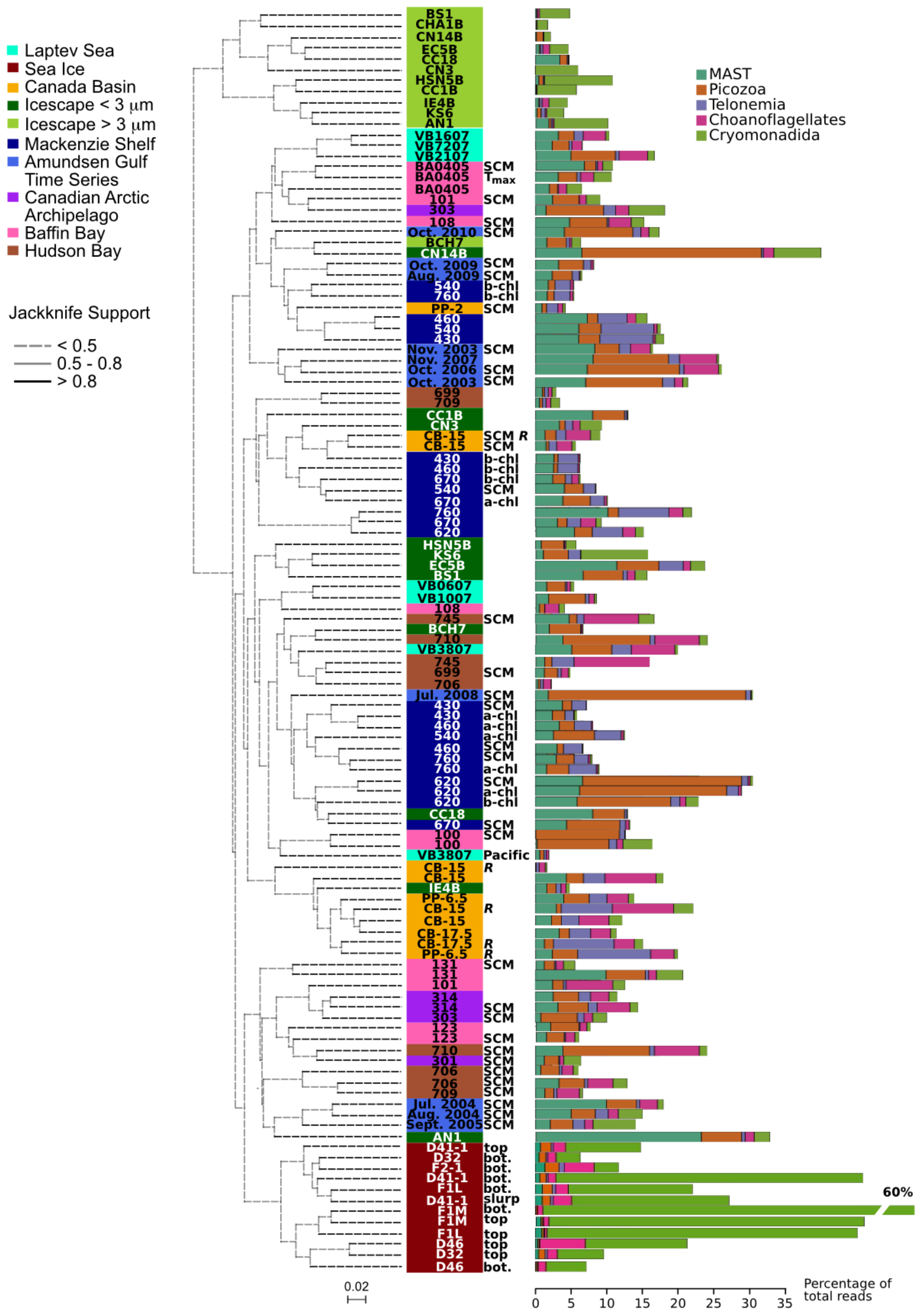

Figure 9. UPGMA tree indicating the clustering of samples from different studies in the Arctic Ocean, based on unweighted Unifrac phylogenetic distance of reads from major heterotrophic flagellate groups. Major groups are shown as a proportion of all eukaryote reads. Unless otherwise indicated, samples come from surface waters and use DNA as the template molecule. Abbreviations for the exceptions are as follows: subsurface chlorophyll maximum (SCM), above SCM (a-chl), below SCM (b-chl), RNA used as template molecule (R), bottom 0 to 300 mm of the ice core (bot), next 300 to 600 mm of the ice core (top), sample taken by a diver from under the ice using a slurp gun (slurp).

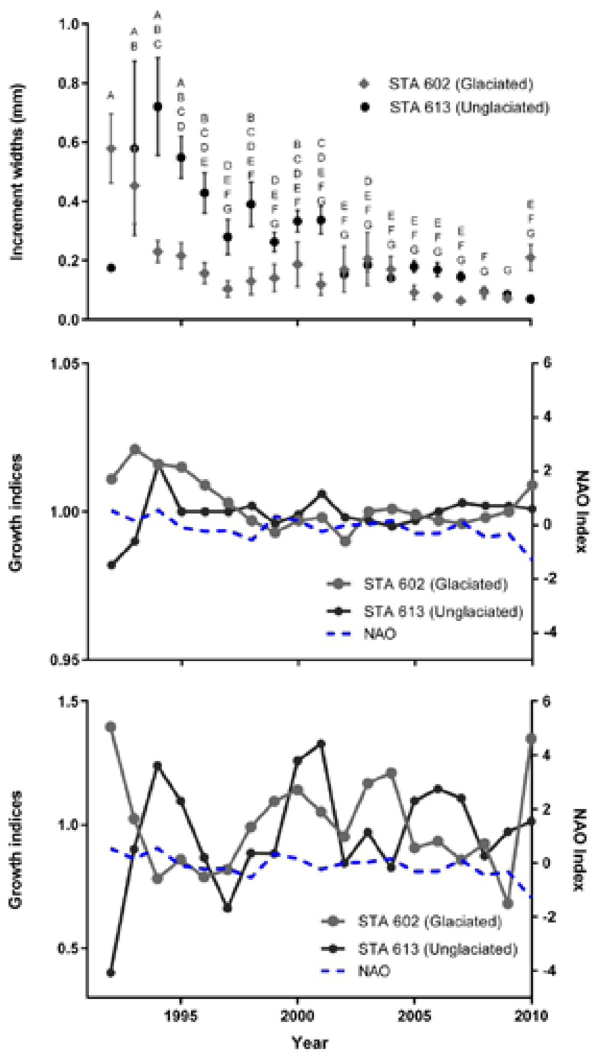

Figure 10. Growth layers analyzed by sclerochronology. Shells of the Portlandia arctica collected in the subarctic fjords Nachvak and Saglek in Northern Labrador.

DISCUSSION

For the offshore Beaufort Sea, previous work had shown that freshwater-induced increases in stratification led to a shift toward small picophytoplankton and bacterioplankton in late summer, possibly leading to reduced vertical export and a less efficient food web (Li et al., 2009). However, in the coastal domain covered by our dataset, diatoms have maintained their dominance of annual NCP. This difference between the two studies can be explained by the fact that our data integrate the entire growth season, including the spring bloom period, whereas those of Li et al. (2009) are snapshots taken during the post-bloom period in summer, when diatoms are not expected to dominate. The difference can also be due to different regimes of stratification between the study areas. The accumulation of freshwater and the strong decreasing tend in surface salinity observed inside the Beaufort gyre offshore does not extend to the coastal region of Amundsen Gulf, where salinity remained relatively invariant at the surface (our Figure 1). In this region, median diatom-driven NCP rose from 12.6 g C m^{-2} in 2003-2004 to 19.8 g C m^{-2} in 2010-2011 (using a C:N conversion factor of 7.1), increasing by 1.6 fold the amount of nutritious organic matter available to consumers and/or export to the deep ocean and the benthos. Because this increase coincided with a deepening of the nitracline (i.e. the base of the nitrate-depleted surface layer) and subsurface chlorophyll maximum (SCM), but a lack of change in surface salinity (i.e. an indication that stratification and vertical mixing have not changed in the areas), we surmise that diatoms associated with subsurface chlorophyll maxima were consuming nutrients over a greater depth of the water column. This interpretation is consistent with reported increases of 9.4, 8.0 and 3.3% yr^{-1} in the irradiance penetrating the upper water column for the months of June, July and August for the period 1998-2009 (not shown here but see Table 2 in Bélanger et al., 2013). Because this change in NCP occurs in the SCM, below the layer visible for satellites in space, we do not expect it to be detected by remote sensing. Indeed, the analyses of temporal productivity trends published of Arrigo et al. (2011) and Bélanger et al. (2013) are inconclusive for the area.

By contrast, data from northern Baffin Bay imply a drop in diatom-mediated NCP from 63.6 g C m^{-2} in 1997-1998 to 21.6 g C m^{-2} in 2009-2011, reaching low productivity levels that are nearly on par with those of the southeast Beaufort Sea (Figure 2). Although this result integrates the entire growth season, it matches the discrete observations of declining phytoplankton biomass and production during late summer/early autumn (Figures 5a-c), suggesting that productivity levels are lower during the spring bloom but for the rest of the season as well. This is suggestive of reduced mixing and upward nutrient supply in the area. Such a change is consistent with declining surface salinities and increased stratification of the water column during the study period, which can be related to freshening of Canada Basin source waters for the west (Yamamoto-Kawai et al., 2009a) and accelerated Greenland glacier melt in the east (Harig and Simons, 2012). A change that affects mixing and upward nutrient supply to the upper euphotic zone should be visible from space, which is indeed the case. The results shown in Figure 5 and in Bélanger et al. (2013) showed a decline in peak chlorophyll-a biomass and annual productivity in the North Water.

The study of Bélanger et al. (2013) showed positive trends in May and negative ones for the rest of the summer season, suggesting a change in the timing and duration of the blooms. Such a change is evident in Figures 4 and 5, which show that the phytoplankton bloom now occurs earlier (~ 3 weeks). This change in timing can potentially cause a mismatch between primary producers and pelagic grazers (Edwards and Richardson, 2004). This is consistent with the recent increase in the growth rates of benthic bivalves in the North Water (Gaillard et al., in prep), which may responds to higher fluxes of freshly produced organic matter escaping pelagic consumption. In this regard, a more detailed satellite study might be helpful to reveal the extent to which the length of the open water period together with wind-driven mixing events may modulate the duration of phytoplankton blooms in the NOW Polynya. The new molecular approaches developed to identify and track the distribution and abundance of microzooplanktonic grazers (HNC, Figure 9) will provide valuable tools to understand this type of change. Among those, phylotypes with restricted distributions, a quality for good indicators, are more likely to be found among taxa of larger cell-size, such as Cryomonadida and Telonemia.

The presumably important role of vertical stratification and mixing regime in the changes observed in the North Water is possibly widespread throughout the eastern Arctic. We showed that in Labrador fjords, the seasonal variations in phytoplankton dynamics were also mainly controlled by the strength of vertical stratification in addition to seasonal differences in daylength. Benthic taxa as the bivalve *P. arctica* also present significant difference between the fjords especially in term of annual growth rates. But rather than stratification and daylength, the disparity in *P. arctica* population was potentially due to the efficiency of vertical organic matter export to the seafloor in some years. The lack of overall trend in growth indices over time (Figure 10) suggests that productivity levels in Nachvak and Saglek fjords are variable between years but have not changed much between the early nineties and 2010.

CONCLUSION

Changes in the physical environment had regionally contrasted impacts on biological productivity in the Canadian Arctic. While increasing light availability apparently led to greater productivity in the subsurface phytoplankton layers associated with the nitracline in the Beaufort Sea, increased stratification in northern Baffin Bay has led to a drastic decline in different indicators of productivity. It is noteworthy that the various in-situ (seasonally-integrated estimates of nutrient consumption and point estimates of phytoplankton parameters late in the growth season) and remote-sensing (annual estimates of primary production and seasonal time courses of chlorophyll-a standing stocks) tell the same story.

The North Water Polynya in northern Baffin Bay has been considered as a secular oasis of biological productivity in the eastern Arctic (Tremblay et al., 2006). It is now becoming oligotrophic in response to increasing stratification and reduced mixing and/or upwelling. The shift from a diatom-dominated community to a flagellated-dominated one may have detrimental consequences on grazers and the large populations of apex consumers (birds, bears and whales) that locally depended on the herbivorous food web (Strom and Fredrickson, 2008).

A first assessment of phytoplankton dynamics in Labrador fjords now provide a reference point to detect changes of the type we have evidenced for the Beaufort Sea and northern Baffin Bay. As in the latter, phytoplankton dynamics in these fjords are strongly influenced by vertical stratification, which is highly sensitive to alterations of the overall freshwater balance at the large and local scales. Using sclerochronological indicators of growth for the bivalve *Portlandia arctica*, which depends on food supply from above, we propose that the productivity of at least two Labrador fjords has been high and not clearly impacted by climate oscillations and long-term environmental change since the early nineties.

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SECTION II. TERRESTRIAL SYSTEMS

Section II is composed of nine ArcticNet research projects covering several biological and physical components of the Canadian Arctic terrestrial systems.

PERMAFROST AND CLIMATE CHANGE IN NORTHERN COASTAL CANADA

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High Arctic ice wedge polygon ecosystem dynamics in a changing climate
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Yannick Duguay, Doctoral Student (Institut national de la recherche scientifique - Eau, Terre et Environnement)
Use of RADARSAT-2 and TerraSAR-X Data for the Evaluation of the Snowpack Characteristics in Subarctic Regions

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Late Quaternary paleoenvironmental dynamics on the eastern Beringian edge (PEBE)
Tania Gibéryen, Doctoral Student (Centre d'études nordiques)
Planning of communities on permafrost in Nunavik
Étienne Godin, Doctoral Student (Université de Montréal)
Maxime Jolivel, Doctoral Student (Université Laval)
Érosion du pergélisol, transfert sédimentaire et sédimentation côtière: région de la rivière Sheldrake, côte est de la Baie d'Hudson
Marie-Ève Larouche, Doctoral Student (Université Laval)
Caractérisation et étude du régime thermique du pergélisol à la mine Raglan, Nunavik
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Andrée-Sylvie Carbonneau, Masters Student (Centre d'études nordiques)
Évolution géomorphologique holocène et caractérisation du pergélisol dans la communauté de Pangnirtung, île de Baffin, Nunavut
Émilie Champagne, Masters Student (Université Laval)
Conséquences de la tolérance au broutement du bouleau glanduleux sur les ressources alimentaires du caribou
Marc-André Ducharme, Masters Student (Centre d'études nordiques)
Caractérisation du pergélisol à l'aide de la tomodensitométrie: étude exploratoire
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Measurements of permafrost greenhouse gas emissions with a new closed chamber automated system
Julie Leblanc-Dumas, Masters Student (Centre d'études nordiques)
Quaternary geology and permafrost characterisation, Hall Peninsula, Nunavut
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Caractérisation du pergélisol en vue de la réfection et l'adaptation au changement climatique de l'aéroport d'iqaluit, Nunavut
Mélissa Paradis, Masters Student (Université Laval)
Maude Pelletier, Masters Student (Université Laval)
Les impacts thermiques et géomorphologiques de l'arbustification d'un paysage pergélisolé, Umiujaq, Nunavik
Laurence Provencher-Nolet, Masters Student (Institut national de la recherche scientifique - Eau, Terre et Environnement)
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Hydrogeological regime at the road test site of Beaver Creek, YT
Maxime Tremblay, Masters Student (Centre d'études nordiques)
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Geomorphology of hypersaline springs in the Canadian High Arctic
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ABSTRACT

This project analyzes how landscapes, ecosystems and human infrastructures are affected by the terrain degradations that take place as permafrost is affected by climate change and as economic activity expand over the land. Permafrost is the foundation upon which northern ecosystems and communities rest and upon which infrastructure is built. The study of ground ice in the permafrost requires knowledge of surficial geology, periglacial landforms and the heritage of past climate conditions and geological processes; it is done with a variety of techniques which include remote sensing, drilling, laboratory analyses, geocryological characterization and GIS applications. Ultimately an assessment of ground ice at a much better resolution that what currently exists will have to be made to support the development and the environmental safeguard of the Arctic.
This project already made continuing and important progress toward that goal. As a physical component of ecosystems, the sensitivity of permafrost is regulated by numerous factors, including air and soil temperatures, snow cover, surface and subsurface hydrology, organic soil layers, vegetation and snow cover, all factors that are regulated by the climate and are themselves affected by change. In this project, changes to the landscape as a result of the changing permafrost temperatures are monitored, including the development of landforms such as landslides, changes in vegetation patterns, modification of drainage patterns, coastal erosion, release of carbon and production of greenhouse gases. In 2014, our research covered those topics, both as fundamental and applied research at many key sites across the Arctic, particularly in southern Baffin Island (Iqaluit airport), on Bylot Island (thermo-erosion and ecological changes), Ward Hunt island (water tracks and ecology), Hershel Island (retrogressive landslides), Eureka (massive ground ice, ice wedges and landslides), Beaver Creek (Alaska Highway), Salluit (road engineering and ecosystem respiration), and Umiujaq (snow-vegetation-permafrost dynamics). Mapping of potential for construction on permafrost was advanced in eight communities of Nunavik (Kangiqsualujjuaq, Kuujjuaq, Aupaluk, Quaqtaq, Kangiqsujjuaq, Ivujivik, Inukjuak and Umiujaq). Our mapping and predictions of ground temperature changes in Arctic communities are used to formulate adaptation strategies and for planning land management. The project also incorporates a major education and outreach initiative for training Inuit community managers on permafrost principles and for producing innovative computer-based pedagogical material for schools for training the upcoming generation. In the coming years, funding permitting, more impetus shall be put on supporting the development of Inuit communities and the maintenance of infrastructure over permafrost.

KEY MESSAGES

Geocryology and geomorphological processes

- Massive-ice and wedge-ice terrains are likely more widespread than previously envisaged by the research community in the continuous permafrost landscape of the Canadian High Arctic and are more and more affected by thermokarst and thermo-erosion.
- Thermo-erosion of gullies in the continuous permafrost zone leads to a re-equilibration of landscape features accompanied by the growth of new ground ice in depositional areas and instauration of new thermal regimes across the landscapes.
- Detailed long term studies on the thermokarst gullying cycle provide a necessary understanding for hazard assessments and eventual design of control and remediation measures in inhabited regions affected by the decay of ice-wedges networks.
- Subsurface water flow through the active layer and across unfrozen terrain units in discontinuous permafrost is an important mode of heat transport that reaches underneath infrastructures such as roads and runways. More research is needed to better quantify this process and design practical solutions in support of infrastructure maintenance.
- Describing, understanding and quantifying geomorphological processes acting on permafrost degradation lead to a better understanding of the carbon cycle in Arctic terrains. Our research results can be used to assess local carbon stocks sensitive to permafrost degradation and add precision to global meteorological modelling of climate changes.
- Destabilization of old buried glacier ice found on Bylot Island and elsewhere through the Arctic triggers severe processes of permafrost degradation giving rise to large retrogressive thaw slumps, massive delivery of sediments in hydrological systems and major changes in landscape topography.
- Identifying and delineating relict glacier ice bodies that are likely more abundant than previously known will become a major issue for large scale industrial projects in the Arctic, since they are very sensitive to perturbations and to climate warming, as shown actually by the multiplication and spreading of thaw slumping.
- On Ward Hunt Island under the coldest climate of Canada, the study of Ward Hunt Lake's watershed dynamics shows that the presence of water tracks – un-incised channels of preferential groundwater flow – have a significant impact on soil temperatures and on water quality in the lake. The peculiar dynamics of the active layer in this environment affected by surface and shallow subsurface water flows needs to be better understood as it is closely related to cyanobacterial mats and nutriments transfers in this extreme environment.
- Ground subsidence and landform change have increased dramatically in the last few years, threatening the integrity of the area surrounding Environment Canada's Eureka Weather Station. Landslides over huge amounts of massive ground ice in the permafrost and subsidence over the dense ice wedge network are key factors.
- The salt dome formations on Axel Heiberg Island, NU, create unique permafrost conditions and hypersaline spring water temperature at the Stolz Diapir was always measured between -10 °C to -15 °C during the period November to April regardless of air temperature (which went as low as -40 °C).

Impacts of climate change on tundra and ecosystems

- At a local scale, once initiated, a diminution of water availability in drained polygons changes plant distribution and cover within a few years. On the contrary, active layer deepening over ice wedges in tundra polygons creates new localized wet ecosystems.
- In Umiujaq, in the discontinuous permafrost zone, the transition from tundra on permafrost to spruce forest without permafrost in the thermokarst process took place over a period of about 90 years, the last 30 years having witnessed the fastest rate of decay. Temperatures got warmer at the interface between snowbanks that got thicker with ground settlement and shrub growth. At a point in the chain of processes, a slight heat flow to the ground was created at the snow/soil interface, maybe associated with increased microbial activity. Organic layers got thicker and the soil evolved from a Cryosol (poor soil on permafrost) to a Luvisol (richer soil without permafrost). The original carbon-poor ecosystem on permafrost evolved into a carbon-rich one through the transition.
- Mapping by remote sensing reveals that in Nunavik (Umiujaq region) newly formed thermokarst lakes gradually disappear or diminish in size over about three decades due to draining, drying, paludification and encroachment by shrub. This should affect the duration of impacts of thaw lakes on greenhouse gas emissions (CH_4) on that longer timescale.

Research applications and socio-economic impacts

- Progress were made on a graphic, animated model for teaching permafrost thermal regime to be used as a teaching tool in Inuit communities and schools. This teaching model called PermaSim is now operational and was demonstrated at the Arctic Change conference in Ottawa in December 2014. This application is part of a more complete package of course material for teaching the basics of permafrost science in northern communities.
- Consultations on recently produced permafrost maps were held in four communities of Nunavik in April 2014 and feedback from users are now taken into consideration. The maps raise a lot of interest and some communities are increasingly taking control of land management and decision on the types of foundations for housing.

Methodological advancements

- After two years of operation, the Fiber Optics Distributed Temperature Sensing system installed under a repaired road (3.4 km of cable) in Salluit is yielding very good results. Temperature monitoring every meter along the road allows early detection of local seeps and heat source that create risks for road stability. This experiment is a first in permafrost science and engineering. The Québec department of transport is already considering corrective and preventive measures at the “sensible” sections of the road detected by the technology.
- Progress was made in the use of CT-scan in permafrost characterization. Excellent correlations were obtained between values of thermal conductivity of permafrost cores obtained at Laval from CT-Scan (200 X 200 X 600 microns resolution) and physical measurements in a conductivity cell, with acceptable measurement precision and errors. The results actually allow the use of the methodology in engineering projects. However tests done at much higher resolution (1 micron) done by the Montreal team show much better performance in assessing the volumetric water (ice) content of frozen samples. Errors in quantitative determination of permafrost thermal properties will eventually be further

reduced as this is a defining variable of thermal properties. Advances in the use of the CT-scan technology shall have importance for both fundamental and applied research.

- Helicopter-borne high-resolution photography and a photogrammetry software linked to the Calcul-Québec supercomputer service was used to develop high-resolution (cm resolution) orthophoto mosaics and DEM of periglacial terrains. This cost-effective method is a great alternative, although at a slightly coarser resolution, to lidar imagery and yields a better product than high-resolution (0.5 m) satellite imagery. A down-scaled permafrost physical model was developed in Montreal to study the thermal impact of sub-surface water flow on the ground thermal regime. Operation of the model allowed for comparing the effectiveness of convective heat transfer over conductive heat transfer and developing a database of Peclet number for various types of soils, which is used in fully-coupled numerical heat transfer models.
- New numerical models in development will help to get a more precise estimate of heat and mass transfers and will allow for better estimating the extent and rate of permafrost degradation and the costs related to the maintenance of the infrastructures.

OBJECTIVES

In 2014-2015, the main objectives of the project were in continuity with the projects' long term objectives of increasing permafrost knowledge in Canada and improving scientific approaches for its characterization and for understanding the processes associated with transitional changes due to climate warming. We aim at developing knowledge on permafrost distribution, properties, thermal regime and ecological relationships over various terrain and climate conditions across the country. Our approach includes mapping and detecting terrain surface properties using remote sensing, mapping and quantifying physical permafrost properties in the geological and climate context, measuring rates of changes and degradation (or thermokarst), understanding and modeling heat transfer processes (conducive, convective and advective), and assessing impacts of permafrost thawing on ecosystems, including carbon and greenhouse gases releases in the environment. The main beneficiaries of our research are the Inuit communities that are built on permafrost and that are facing the challenge of housing expansion and urban development. Other beneficiaries are the owners of major infrastructures such as airports and roads, namely territorial governments and the government of Québec.

We advise communities and governments for adaptation plans in the context of climate warming.

This report explains in detail the research results associated with the key messages. However a final section is dedicated to the work done in producing training material for Inuit actual and future leaders.

INTRODUCTION, ACTIVITIES AND RESULTS

Geocryology and geomorphological processes

In 2014-2015, the research of the team members addressed the broad question of the stability of ice-rich landscapes, changes in ground thermal regime and the dynamics of typical permafrost features such as massive ground ice, ice wedge polygons, active layer detachment slides and thermokarst.

Massive ground ice bodies

Field observations carried by our NIs and comparisons with previous observations highlight how much more widespread than generally thought are the areas of the North that are underscored by massive ground ice. As reported last year, the sheared structure of the ice and till inclusions in the extensive buried ice bodies found in the Arctic Archipelago and in the Mackenzie region indicate that a large fraction of this ice consists of buried remnants of the Quaternary glaciers. The occurrences of massive ice are often made evident in the headwalls of retrogressive thaw slides, i.e. slides that expand incrementally over the years until they eventually reach equilibrium along the sloping terrain and become inactive. Pollard's team kept monitoring headwall retreat of theses slides in the Eureka region (Figure 1) and at Hershel Island. In the Eureka region, the retreat was somewhat slower in 2014 than in the two previous years due to cooler climate conditions that provoked less melting of the ice exposed in headwalls. At Eureka, those slides and the mudflows that extend from them are beginning to put infrastructure at risk.

In the Qarlikturvik valley at the southwest end of Bylot Island (Nunavut), in Sirmilik National Park, the close examination of the tabular ice bodies also led to the hypothesis of a glacial origin. Remnants of glacier ice represent potential sources of information on past climates and glaciologic processes at the time of ice formation. These types of terrain are extremely sensitive to surface disturbance, especially if the ice is close to the surface. The objective of S. Coulombe's Ph.D thesis project is the reconstruction of geomorphic, glacial and climatic conditions in the Eastern Canadian Arctic based upon permafrost ground-ice. In 2013, a multicriteria approach was used for a physicochemical characterization of buried ice exposures in order to better determine its origin. Combined to the analysis of ice petrofabrics and cryofacies, high-resolution images of the internal structure of the ice cores were obtained using a computed tomography (CT) scanner. Examinations of ice cores samples revealed different cryostructures of glacial origin: 1) clear to milky white ice, with interlocked crystal boundaries (englacial ice); 2) suspended ice-rich sediments (basal ice) and 3)

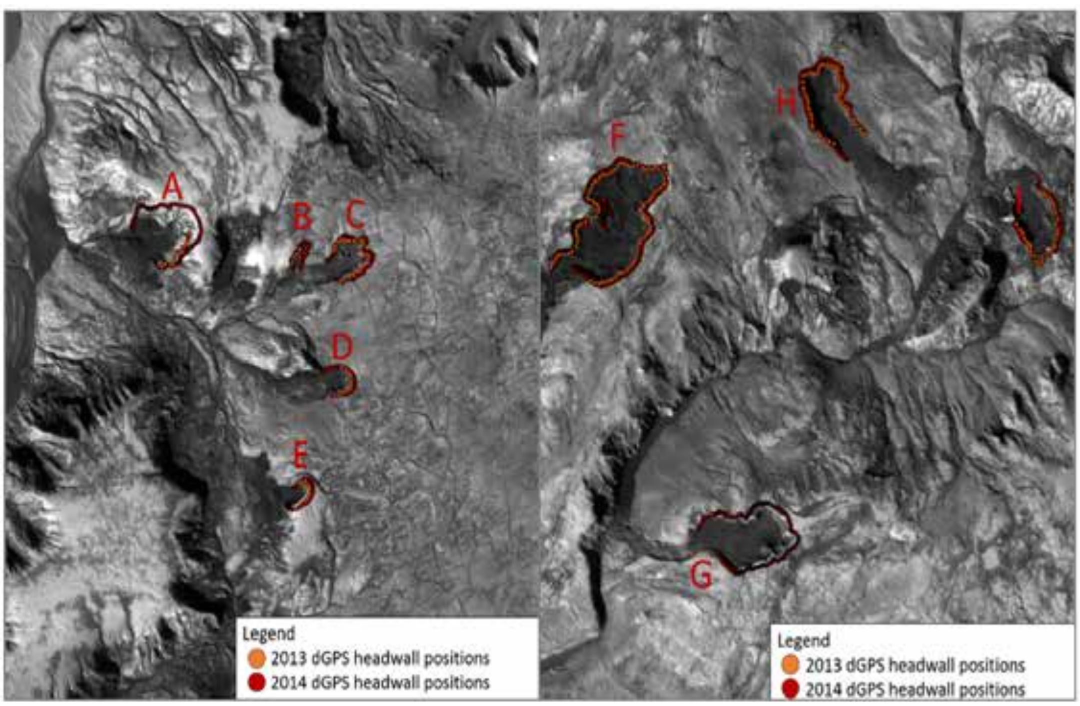

Figure 1. dGPS points detailing the location of several thaw slumps headwalls around the Eureka Weather Station on right and the Dump area on left overlain on WorldView2 imagery from 2012 (Ward with NI Pollard).

lenticular ice-rich permafrost (basal ice). Based on a several diagnosis criteria (cryofacies, ice-soil contact, ice crystals, gas inclusions, sediment inclusion, deformation structures), this project research aims to develop a classification to help identify buried glacier ice types. The need to better characterize massive ground ice, to understand its preservation context and its geomorphological context is taking some importance because its occurrences will affect future development projects either by risk of collapse or risk associated with the major slides and extensive slope failures, with attendant damages to infrastructures.

The impact of a deeper active layer on tundra polygons and ice wedges

The widespread occurrence of ice wedges near the soil surface makes vast stretches of Arctic landscapes sensitive to ecological transformations as the increase in active layer generates localized accentuated thaw settlement along the sides of tundra polygons. This process generates myriads of new small ponds that may merge with time and form larger lakes. The ice wedges are also very sensible to thermal erosion when running water flows in runnels along polygon sides, a process that creates network of gullies leaving a hummocky topography of multiples mounds called baidjaracks. Thermo-erosion along ice wedges can also lead to the drainage of lakes by opening new discharge outlets in a matter of hours.

Ice wedges are particularly sensitive to increased summer temperatures because the stratigraphic position of the top of an active ice wedge is generally controlled by the depth of seasonal thawing (the base of the active layer). Its location at or near the frost table and its ice content close to 100% means that any increase in the active layer results in subsidence along the top of the wedge relative to the enclosing permafrost. Throughout much of the Arctic enlarged troughs are not unusual and thaw degradation along the top of ice wedges leads to the formation of a larger number of high-centred polygons and tundra ponds. In some regions such as Eureka Sound Lowlands and in other polar desert settings, many ice wedge networks used to lack surface trough structures and in some cases did not even have any surface expression at all. However, since 2005 many of apparently stable ice wedge polygons at our ground ice monitoring sites have started to display thaw degradation and enhanced troughs structures.

An important focus of our work on ground ice is the characterization of ecological changes related to ice wedge subsidence and modeling their stability relative to the surrounding terrain. Due to the abundance of ice-wedges and the associated changes we have found in moisture regimes, vegetation communities, and soil nutrients, we predict ecosystem heterogeneity to increase across the high Arctic with further climate change. Subsidence facilitates the accumulation of moisture that promotes plant growth which goes on to insulate the area from further warming from the air; these new plant communities are distinct in community composition. Finally, these wetland-like plant communities have changed the soil chemistry of thermokarst areas and further contributed to the increasing heterogeneity of the ecosystem. The results obtained so far suggest that an initial climate-warming disturbance to the thermal regime of High Arctic ice-wedge polygon systems shall result in long-lasting and significant effects on the polar desert landscape. When ice-wedges decay they contribute moisture into a dry environment, but importantly the ground subsidence over the ice-wedge results in a depressed microtopography that may amplify the accumulation of moisture during precipitations. These depressions form novel niches that act as a relative refuge for colonizing vegetation - creating an “oasis” ecosystem distinct in abundance, composition, and function from the surrounding polar desert. In turn, these colonizing communities have likely produced an alternative ice-wedge stable state.

We make the hypothesis that stabilized thermokarst (melt) areas have shallower active layers and degraded ice-wedges, with decreased vegetation diversity but higher abundance due to a changed hydrological balance. These shifting plant community patterns, soil characteristics and active layer dynamics will have significant ecological impacts both on the far northern polar desert landscape and in areas of widespread networks of ice wedges.

Work at the Iqaluit airport also shows that the thawing of ice wedges can affect major infrastructures. The thawing along the natural network of ice wedges buried during infrastructure construction in 1943 actually generates a pattern of troughs in the runway that requires major repairs in order to meet international standards of runway surface quality (the IRI or International Roughness Index). In 2014, Allard's team was involved not only in precision mapping and sizing of ice wedges under the infrastructure but in consultations with the owner/contractor on possible techniques for repairing the damages and guaranteeing long term stability. Monitoring quality assessment and performance of the repairs and resurfacing are in the plans for an extended collaboration with the operator (Arctic Infrastructure Partners) for the coming years.

Erosion of ices wedges

The objectives of this project (E. Godin, Ph.D candidate, A. Veillette, M.Sc candidate) are to characterize the processes implied in gullying erosion until stabilization in a landscape evolution perspective. Impacts (mass transfers, small stream hydrology and ground moisture changes, active layer depth changes, ice content changes), distribution, shape, state (active/stable) and rate of erosion over years and decades are focused on to seize the full spatio-temporal cycle or erosion.

As of 2013, 35 gullies breached 1401 polygons in a terrace located in the valley of glacier C-79 (Bylot Island). Historic aerial photography (1:15000, 1972) provided information on water tracks and small streams paths located near the location where a gully was initiated in 1999. Consequently, we observed a transition from a surface runoff dominated hydrologic system towards a channelized flow system following the initiation of gullies in 1999. 3D field surveys of gully contours and cross-section with a differential GPS provided an estimated 158 000 m^2 eroded area with 200 000 m^3 of eroded volume. 229 000 m^3 of water was measured at the outlet of a single gully, often transporting sediments, nutrients and carbon toward another system. Upcoming research will focus on water quality and sediment transport.

A polygenetic ice-wedge was sampled for each ice-type (foliated ice, tunnel ice) and $\delta^{18}O$ determinations will be performed to better understand the conditions of water trapped in tunnel freezing.

From 2010 to 2013, linear retreat measurements for all 113 axis of three studied gullies, grain-size analysis and active layer thickness, humidity and temperature were used for spatio-temporal characterization. Each thermo-erosion gully incised a different surficial deposit. Extent and number of erosion axes varied greatly between organic-rich (94 erosion axes on 24800 m^2), colluvial (6 axes on 7366 m^2) and eolian environment (13 axes on 4095 m^2). The results show that thermo-erosional gullies have distinct morphologic and dynamic characteristics depending on their depositional environment.

Ground penetrating radar surveys operated in 2014 on a stabilized gully is currently in data processing and extraction of permafrost cores in 2015 will allow its validation along with the creation of a tridimensional soil profile throughout the stabilized gully. It is also expected to identify aggradational ice that must have forms in sediments in the depressions.

Mass movement and thermo-hydrological dynamics of high-arctic lake watershed

On the Northern coast of Ellesmere Island, collaborative studies of the NEIGE project (Northern Ellesmere Island in the Global Environment, W.F. Vincent, Laval) concerning periglacial mass movements and watershed geochemistry have been conducted around Ward Hunt Lake. These studies are linking watershed organization and mass movement processes to the benthic ecosystems and physical characteristic of Canada's northernmost lake. A large component of the flow of water, carbon and mineral nutrients from the tundra to the lake takes place along the dense parallel network of water tracks on a shallow active layer (Figure 2). The flow of water through these intermittent streams cools the soil and prevents the deepening of the thaw front during the warm season. Those data therefore contradict thermo-erosion studies in other settings where water flow accelerates ground thaw. They also point out how little is known about active-layer dynamics during the very cold summers of the extreme Arctic. The transfer of nutrients and suspended material from the watershed to the lake depends strongly on flow paths. Near-surface flow in water tracks have a higher concentration of suspended sediments, nitrogen and phosphorus, while surface flow in rills have higher dissolved organic carbon contents. Nitrogen and most of all phosphorus contents are limiting nutrients in Ward Hunt Lake and the presence of water tracks could play a role in the distribution of cyanobacterial mats on the edges of the lake. During the summer, water flowing out of water tracks at the lake margin contributed to accelerate the melting of the lake ice cover, which suggests that they play an unsuspected role in lake ice phenology (Paquette et al., in press).

Solifuction studies at Ward Hunt Island

Solifluction is the slow downward movement of thawed soil in summer over the frozen permafrost. The sliding process over times segregates the fine fraction of the soil which usually concentrates into lobes or tongues at the soil surface. Coarser soil fragments tend to concentrate in parallel stripes ant the front of solifluction lobes. We discovered evidence that the morphology of a stone-banked solifluction lobe, characterized by a frontal and peripheral ridges (composed of coarser material), dictates permafrost

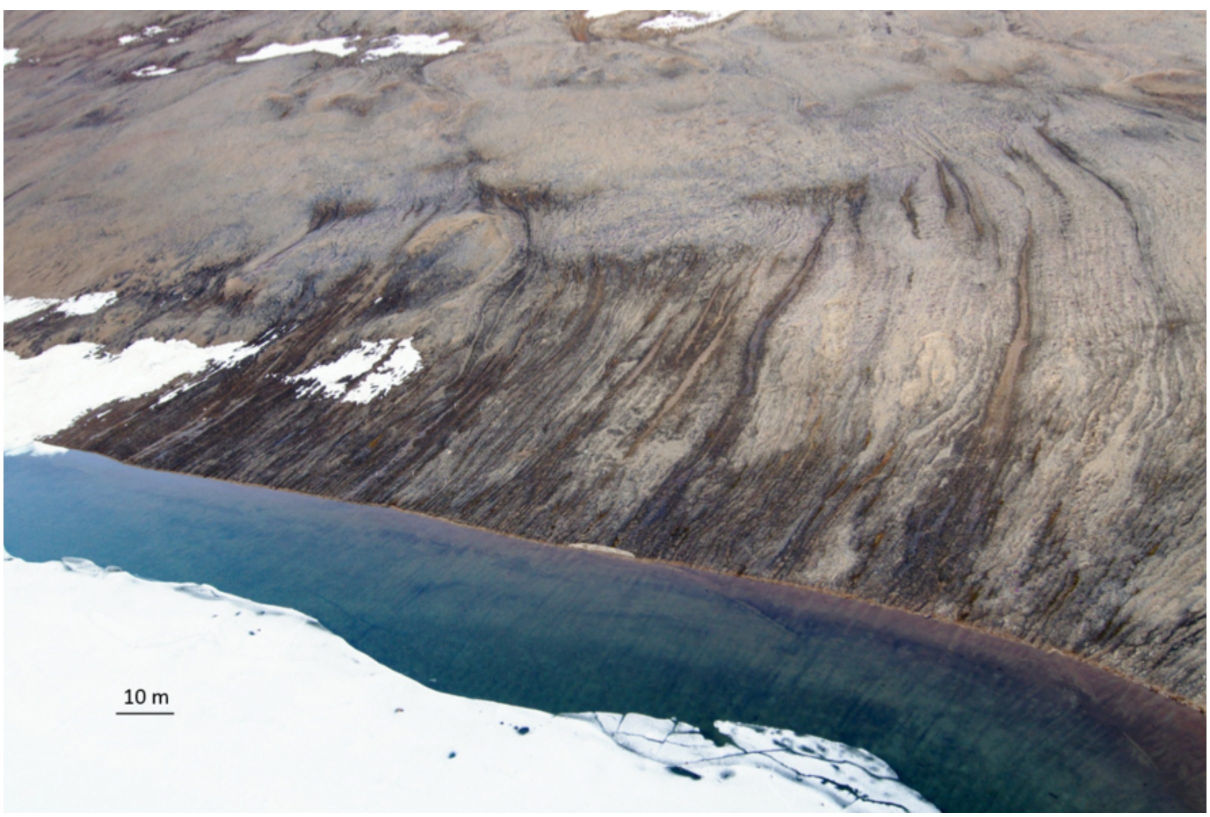

Figure 2. Water tracks of the inshore moat of Ward Hunt Lake showing the impact of water flowing out of water track on lake ice melting. Note the difference with the left portion of the picture without water tracks.(D. Fortier).

cryostratigraphy and spatial distribution of ice-rich and ice-poor cryofacies. On the ridges, the high hydraulic conductivity of the material permits a fast evacuation of subsurface water and the creation of an ice-poor permafrost. Behind the frontal ridge in the central portion of the lobe, longitudinal depressions accumulate finer-grained material covered by mosses and plants that permit a higher retention of water, a shallower active layer and the formation of an ice-rich syngenetic permafrost in accreting sediments. In a context of climate change and active layer deepening, the creation of ice-rich zones may contribute to locally slow down permafrost degradation, due to the important latent heat effect represented by the new volume of ground ice. However, thawing of the coarser material under the ridges will likely be rapid due to the low ice content of the material.

Geology and permafrost

Images obtained by time lapse cameras (one picture taken at noon everyday between July 2013 and April 2014) show that the spring at Stolz Diapir flows year round. These springs are hydrologically active during winter due to the high salt content within the water; indeed spring water is hyper-saline, with concentrations up to 125000 mg/L Na. The geology of the island is characterized by numerous diapiric structures associated with thick evaporate deposits in the Otto Fiord Formation of the Carboniferous Period. It is reasonable to consider these salt structures as potentially causing thermal anomalies within the permafrost and effectively decreasing the depth of permafrost within the vicinity of diapirs.

Impacts of climate change on tundra and ecosystems

Erect shrub growth in the High Arctic

The High Arctic is generally characterized by its continuous permafrost and prostrate vegetation. Yet erect shrub populations are found in some areas in the southern parts of the High Arctic and a transition from prostrate to erect vegetation would transform high arctic ecosystems. We initiated the characterization of patches or Salix richardsonii at Bylot Island Nunavut (M.Sc Maxime Tremblay, co-supervised by Lévesque/Fortier). In order to understand the main drivers of erect shrub growth in continuous permafrost zones, we sampled 74 plots presenting a gradient of abundance of the erected shrub *Salix richardsonii* through various environments in Qarlikturvik valley, Bylot Island, NU. For each plot, environmental (active layer depth, soil texture, temperature, humidity) and vegetation (shrub dimensions, plant cover and composition) features were measured. In addition, humidity and temperature loggers were set at different depths in plots of high and low shrub density. A time-lapse camera has also been set to monitor snow-shrub interaction. Dendrochronological analyses are in progress to assess minimal age of establishment of two contrasting populations. Preliminary results highlight that the most important patches are found on mineral substrate and where the active layer is deeper. These conditions are frequently associated with channels over alluvial fans, that is in wetter, slightly depressed linear areas that likely receive sediments from upslope, thus providing a potential linkage between permafrost aggradation, ground ice formation and vegetation cover in this dynamic setting.

Densification of shrub cover near the tree line: remotely detectable landscape transformations

Change detection of landcover is an excellent tool to track environmental changes in the landscape. We studied an area near the tree line where high quality permafrost monitoring has been maintained for decades and recent vegetation studies have identified rapid shrub growth. Using remote sensing approaches, it was possible to broaden observations to the landscape and monitor vegetation change in this changing permafrost landscape. Improved detection of land cover changes was made possible by combining remote sensing approaches and field validations. M.Sc student Laurence Provencher-Nolet (M.Sc completed in August 2014) used object based classifications of high resolution aerial photographs (1994 vs 2010) to perform a detection change analysis. Her results confirm the strong increase in shrub cover observed by local knowledge holders. Most vegetation types were transformed by an increase in shrubs that were dominant in 60% of the landscape in 2010 compared to 48% in 1994 (Provencher-Nolet et al. 2015, in press). Very interestingly this analysis also highlighted the transformation of ponds into shrublands (Figure 3). This is likely associated to drainage of these thermokarst ponds that favored shrub colonization of their margin. These results support and strengthen those of Inga May (Ph.D) completed at a broader scale in the same region (May et al. 2015, accepted) and highlight the transformations in progress near the tree line.

Vertical structure of the erect shrub Betula glandulosa in the Sub Arctic: Impacts on vegetation, snow depth and soil temperature

The vertical distribution of resin birch (*B. glandulosa*) above ground biomass was sampled by of 10 cm strata at 22 sites near Umiujaq in summer 2013 (M.Sc Mélissa Paradis, co-supervised Boudreau/Lévesque). Wooden biomass was always greater in the lower stratum (<25 cm). Foliar biomass was distributed in the intermediary strata regardless of shrub height which favors light interception. This implied that leaves were almost absent from the lower strata for higher shrubs.

Winter temperature profiles were monitored hourly in *B. glandulosa* patches with iButtons (Maxim Integrated) distributed on snow sticks (every 10 cm) and direct snow measurements were taken in February 2014. Snow accumulation in sites ranged from 30 to 100 cm. During winter 2013-2014, snow accumulation on sites was positively correlated with mean shrub height. An increase in snow depth significantly warmed soil temperatures during the winter season.

Analyses of shrub growth throughout the landscape at Umiujaq continue. Clearly, growth is not uniform at all sites and nutrient status is a key variable. Soil temperature is associated to nutrient availability and explains in part the variation in shrub growth (M.Sc Marilie Trudel, co-supervised Lévesque/Boudreau). A new M.Sc project was initiated in fall 2014 to quantify the impact of increasing

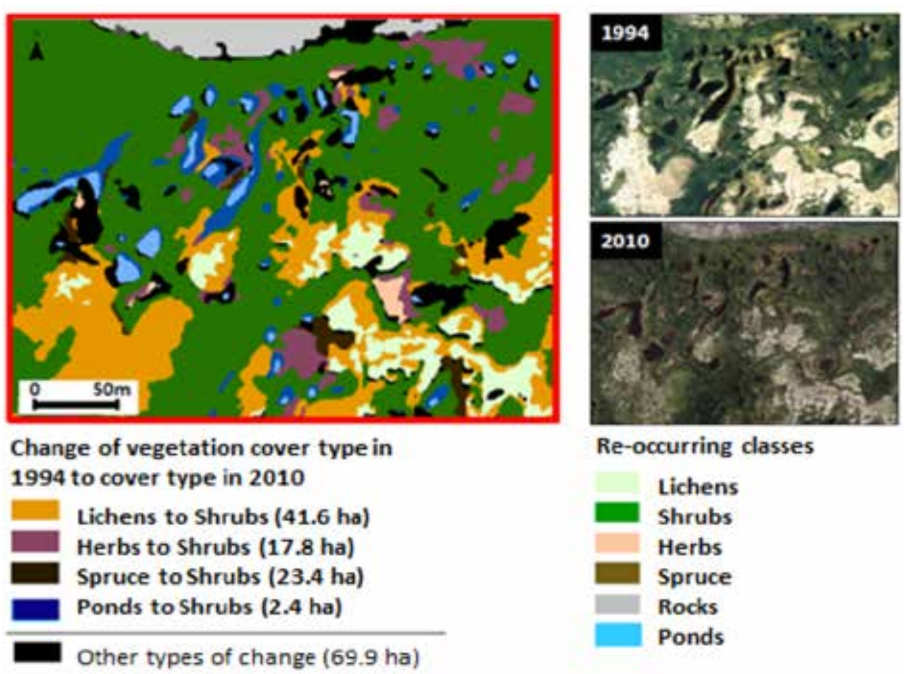

Figure 3. Example of change detection observed near Umiujaq, Nunavik on a small sector of the Tasiapik valley; 1994 and 2010 photographs of the mapped sector are presented to the right (L. Provancher–Nolet).

shrub growth on berry producing shrubs (Isabelle Lussier, co-supervised Lévesque/Boudreau).

Hydrological changes with permafrost disappearance in the discontinuous permafrost zone

In 2014, a hydrological and hydrothermal modeling study (WaSiM model) was initiated in collaboration with the University of Munich (Wang Lingxiao, Ph.D Candidate) in the Sheldrake River watershed to simulate changes in the water balance in response to the dynamics in the hydro-thermal cycle of the subarctic region. The watershed is a 210 km² river catchment in the discontinuous permafrost zone on the east coast of Hudson Bay. For model calibration, model parameters are adjusted to fit measurements at the Sheldrake River gauging station (Jolivel and Allard, 2013) using the NSE efficiency criterion. Temperature profiles available from thermistor cables (in Tasiapik valley) (Nordicana D dataset, CEN) and also active layer thicknesses measured in field campaigns are used to calibrate the parameters in the heat transfer module.

A 10-day field campaign was done in September 2014. In these surveys, soil properties and land cover information were collected; thawing depths and soil moisture at several feature points were sampled through probing to parameterize the hydro-thermal model. Eight sites were surveyed by helicopter. It is anticipated that each monitored site represents the soil type and vegetation cover of one typical landscape unit. More sites will be visited in summer 2015 as this doctoral research will continue in collaboration with CEN\ArcticNet researchers.

Ecosystem changes with disappearance of permafrost

In the discontinuous permafrost zone, climate warming is actually leading to permafrost degradation and concurrent major ecosystem changes. Among other impacts, geomorphic changes due to thaw settlement, expansion of vegetation cover, increased snow depth in thermokarst hollows and the recycling of organic matter and carbon in the transforming ecosystems concur over time during the process of permafrost thaw to a drastic change in ecosystem structure and functioning. In order to make a quantitative assessment of ecosystem changes associated with permafrost degradation and to assess the speed of the changes, we selected six sample plots located on a silty ice-rich permafrost plateau in the Tasiapik valley, near Umiujaq, in Nunavik (Pelletier's M. Sc. thesis co-supervised by NIs Allard and Lévesque). The six plots are representative of the regional ecological time sequence associated with permafrost degradation which includes increasing active layer thickness, thaw settlement, plant cover densification and snow cover change. The rate of transition is assessed by analysis of time-lapse aerial photographs and through dendrochronology on shrubs and trees. Figure 4 provides a synthesis of whole ecosystem change. As permafrost disappears, heat fluxes are nullified or even inversed at the base of the deeper snowpack in winter at the soil surface where humus is accreting. Soil horizons get deeper and in the silty material of the study site the soil was changed from a Cryosol (permafrost with an active layer and minimal organic horizons) to a Luvisol (an evolved soil profile with thicker organic horizons and carbon enrichment). In fact the transition is from an Arctic ecosystem to a Boreal ecosystem.

Ground water and permafrost thermal regime in relation with a linear infrastructure

The objectives of the research (M. Sliger, M.Sc candidate) are to understand the hydrological and thermal responses of a watershed after human disturbance (road, drainage ditch), and to provide new tools for linear infrastructure design intercepting groundwater flow.

This year, a conceptual model of landscape and permafrost evolution since the regional deglaciation was developed to enhance the understanding of the processes happening at the Beaver Creek field site in Yukon (Figure 5). The digital elevation model

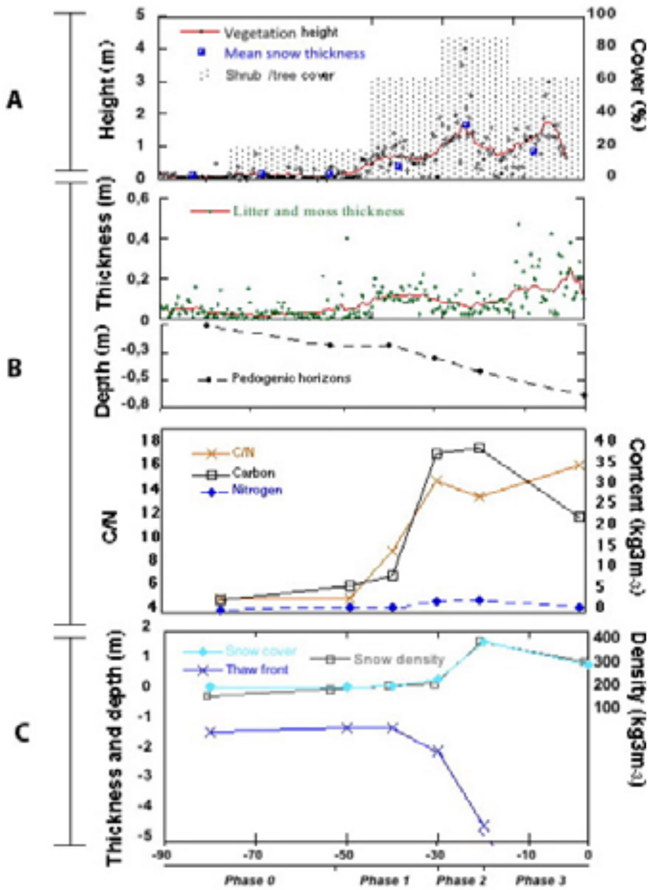

Figure 4. Chronological synthesis of A) ecological, B) biogeochemical and C) physical parameters along four permafrost degradation phases. Mean C and N contents and C/N ratios were calculated for the total active layer (plot 1: 0 to 50 cm; plots 2 to 6: 0 to 60 cm). Vegetation height and litter and moss thickness measurements were taken in the same respecting order and location for each plot. An interpolation curve (red line of graph A) was calculated with the Stineman function (rational interpolation - polynomial) using the respective linear measurements done on the eight cardinal transects.

(DEM) of the site was extended and refined with a precision survey conducted using a differential GPS. Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR) transects were performed on the road and in the natural ground in order to validate the presence of taliks and to represent sub-surface thermal variability of the permafrost. The data will be processed to enlight preferential groundwater flow paths and hence preferential heat flow paths within discontinuous permafrost watershed.

To measure the thawing behavior of a frozen soil under continuous water flow condition, physical simulations were performed in laboratory using thawing cells. These new physical model experiments were useful to understand the behavior of a specific element by controlling all the other parameters. Another new tool to calculate the heat capacity of a given soil was tested with success in the laboratory. The laboratory test results will be used to accurately feed permafrost thermal numerical simulations.

Research applications and socio-economic impacts

Community adaptation to climate warming

Under the Green Plan initiative of the Government of Québec and in partnership with the Kativik Regional Government, preliminary mapping of surficial geology, permafrost conditions (soil texture and ground ice contents, periglacial landforms) and potential for construction was carried on in eight Nunavik communities: Kangiqsualujjuaq, Kuujjuaq, Aupaluk, Quaqtaq, Kangiqsujjuaq, Ivujivik, Inukjuak and Umiujaq. The field work consisted first in meeting with community leaders and managers to discuss needs and expectations for housing, expansion and land management as well as gaining a vision of permafrost related issues. Then previously interpreted maps on air photographs and remote sensing images were validated with field checks, soundings, selected drilling sites and sometimes with heavy machinery (excavators). Soil samples and frozen cores were recovered. Some of the maps that need further field check, particularly more drilling to improve accuracy, will be achieved in 2015. Figure 6 shows the example of Umiujaq.

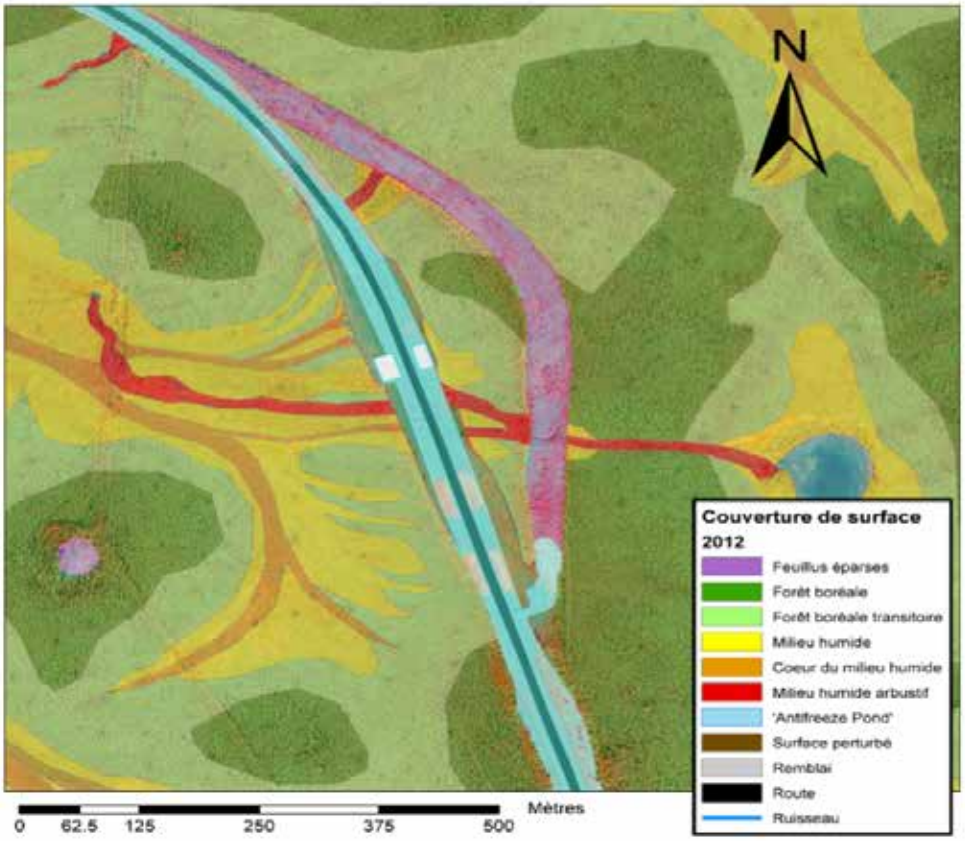

Figure 5. Eco-geomorphological map of discontinuous permafrost terrains (Beaver Creek, YT) showing the interaction between terrain units and the road infrastructure (M. Sliger).

In April, prior to the season's field surveys, a visit of some of the communities was organized and meetings were held at the KRG in Kuujjuaq. This trip was also an occasion to re-visit the community of Kangirsuk which had been mapped previously and discussed the usefulness of the maps as a decision making tool. Issues related to earth sciences, knowledge of permafrost principles and quality of life were discussed. The final question was: when are you coming back to visit us?

The permafrost maps of the eight newly mapped villages were presented and plans for the continuation of the project in 2015 were discussed at a meeting held at Ministère des Affaires Municipales et de l'Occupation du Territoire in Québec city on 10 February 2015 with the participation of representatives of KRG and different provincial departments (Ministère des transports, Secrétariat aux affaires autochtones, Ministère de la faune des forêts et des parcs, Ministère des richesses naturelles, Société d'habitation du Québec).

Methodological advancements

Application of the fiber optics Distributed Temperature Sensing technology

Fiber optics distributed temperature sensing (DTS) is an emerging technology that opens the door on new approaches to study permafrost temperature regime in a variety of environmental settings and engineering situations. In DTS systems, as pulses of light emitted

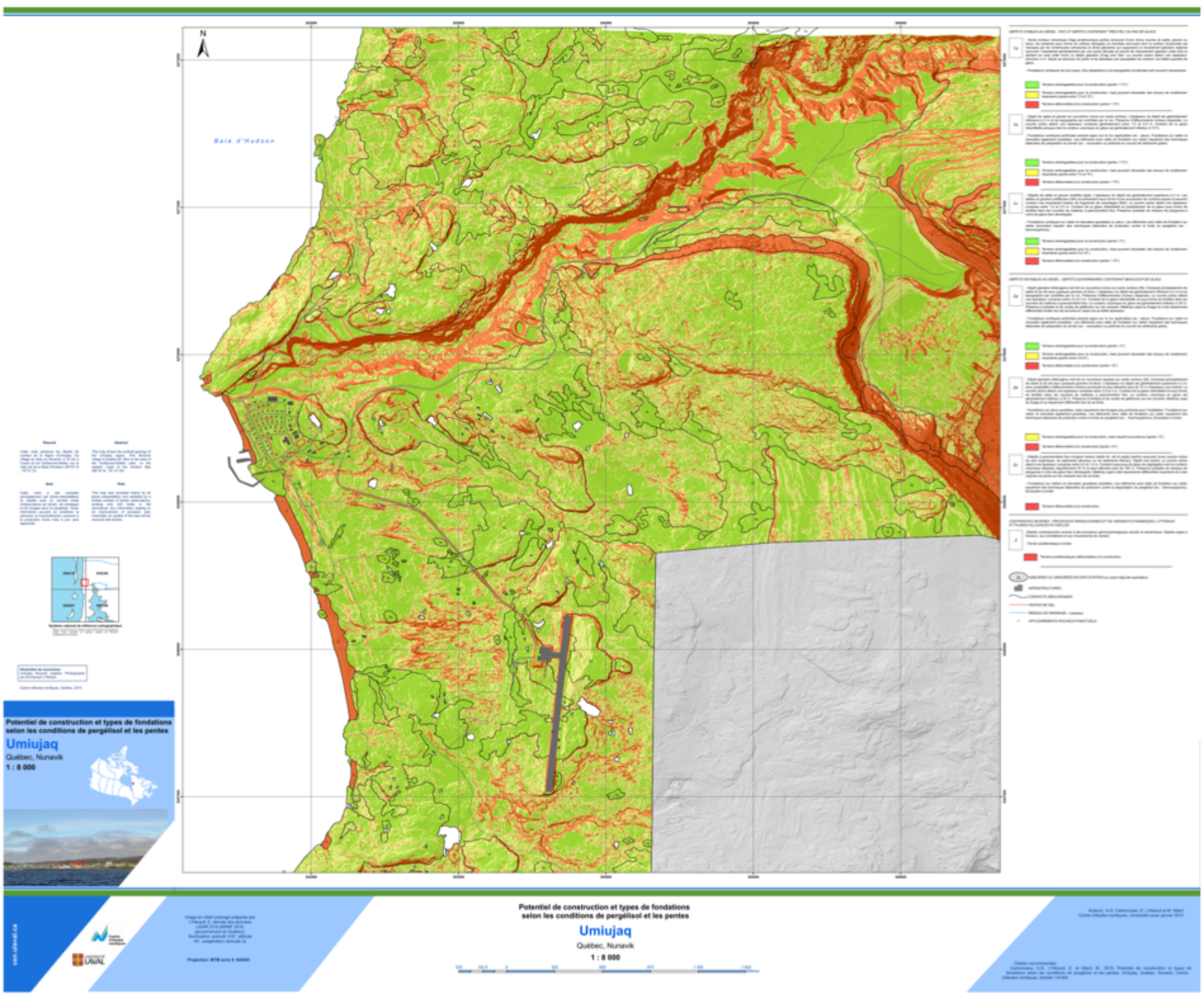

Figure 6. Map of potential for construction on permafrost of the community of Umiujaq, Nunavik.

by a laser travel in a fiber optics cable, a small fraction of the signal is reflected along its course back to the source with a slight frequency shift that is temperature-dependant, thus allowing to measure temperature along the cable by measuring two-way travel time. An occasion to try the new technology arose in 2012 as Ministère des transports du Québec decided to rebuild the Salluit road to the community airport that had been seriously impacted by permafrost degradation. The permafrost beneath the road consists of very ice-rich post-glacial marine silt that puts the road at high risk of deterioration by permafrost thawing following any input of heat that may occur anywhere along its length, the most feared heat sources being snow insulation on shoulders in winter and water seepage underneath the structure in summer. About 900 m long of embankment were rebuilt: specially designed heat drains were buried under one side of the road to cool the embankment under snow in winter. On the other side of the road, the geometry of ditches and culvert was redesigned. In addition to thermistors strings at selected control and sampling sites, a total length of 3.4 km of DTS cable were buried under the embankments slopes on both sides of the road. On the upland side of the road, the cable is buried at two depths (0.3 and 0.8 m) to detect heat carrying water seepage in the ground whereas on the other side it is buried under the heat drain to assess its efficiency in cooling back the permafrost under the road. A section of the cable also measures ground temperature 0.25 deep in the natural terrain several meters off the roadside as a reference. The cable also runs in loops across the road under four culverts. The linear resolution of the system is 0.25 m and the temperature measurement precision is 0.1 °C. The datalogging system was programmed to take readings every 3 hours over a year.

After two full years of operation, the system provided a wealth of thermal data and, indeed, “hot spots” where seeping water infiltrates under the embankment were detected early with the use of the technology. Those sensible points would have remained undetected by isolated thermistor cables. Long-term validation against conventional thermistor cable measurements is being pursued by statistical comparisons. The technology, its implementation, the handling of the large amount of data it generates and the new approach to temperature mapping in time and in space were presented at the Arctic Change conference.

The measurement of permafrost thermal conductivity from CT-scan determinations of permafrost composition

Structural and thermal design considerations when building in the Arctic require precise knowledge of the thermal and geotechnical properties of permafrost. Property values are also necessary as input for the parameterization of heat transfer models and thaw settlement prediction. Following previous studies that showed great potential in using X-ray computed tomography for volume measurements of permafrost components and visualization of cryostructure, an innovative method to measure permafrost thermal conductivity was developed up to an advanced stage (M.A. Ducharme’s M.Sc research). This approach combines proven thermal conductivity models and computed tomography analyses. We use a three-step model that takes into account the soil type, the porosity of ground ice and the cryostructure in the samples to assess the potential of the proposed method. To do so, 19 permafrost samples with different textures and cryostructures, ranging from homogeneous fine-grained soils with stratified ice lenses to coarse-grained diamictons well-bonded with pore ice, were extracted from various sedimentary environments in Nunavik and Nunavut. The core samples were scanned using a Siemens Somatom 64TM scanner at the Institut National de la Recherche Scientifique (INRS) in Québec city. According to the core diameter (100 mm), a voxel resolution of 0.2 x 0.2 x 0.6 mm was obtained. By selecting a range of Tomographic intensity (TI) values corresponding to each of the soil components (sediments, ice, and gas), voxel classification and quantification of the sample components were achieved using ORS Visual © software, therefore providing volumetric contents of the frozen cores. The thermal conductivity tests are conducted inside a cell surrounded by an insulated box at a constant temperature of about -8 °C. Temperature boundary conditions at the top (-4 °C) and bottom (-12 °C) of the cores were maintained with two independent heat exchangers creating a vertical heat flow through the sample. The comparative results between CT-scan derived conductivities and thermal conductivity cell results show a great potential for the method ($R^2 = 0.86$).

Fortier’s team ran similar tests with a higher resolution (1 micron; Skyscan) CT-Scanner. Results show, as expected, that the errors in determining ice contents are much smaller as the higher resolution better allows detection and quantitative assessment of ice in small soil pores. This opens the door to still more accurate determinations of permafrost properties in the future with this instrumentation.

Technological development and test of new soil respiration chambers

At the moment, there are only few means of directly measuring permafrost GHG emissions over long periods of time without an operator and at small costs. The main objective of this master's thesis project by S. Gagnon is to measure permafrost CO_2 and CH_4 emissions in a polygonal peat bog located in Salluit, Nunavik. In order to assess the future impacts of warming on carbon fluxes, GHG emissions were measured under the current climatic conditions and inside open-top chambers (OTC), which can reproduce the climatic conditions expected in about 50 years. In addition, the spatial variations of GHG emissions over the network of ice wedges, from dry tundra polygon centers to wet troughs where ice is decaying, were studied in order to determine the effects of soil water saturation on GHG emissions and composition. This project also aims to develop a new instrumentation: a closed chamber automated system. The goal was to design and build a system capable of taking precise measurements over long periods of time with low-cost gas sensors instead of using conventional ways to measure carbon concentrations such as an infrared gas analyzer and gas sampling with a syringe. In addition, the system was designed to operate autonomously and maintain the integrity of the studied sites.

Four automated closed chambers were used for the project (Figure 7). Three of these chambers were on polygons centers where the soil is relatively well drained. The first site was used for the chamber in natural conditions (C_n) and the second one for a chamber inside an OTC (C_{OTC}). On the third well-drained site, surface vegetation inside the chamber was clipped in order to roughly measure GHG emissions emitted from the soil alone (C_{soil}). The fourth chamber was installed between two polygons, i.e. on an ice-wedge trough where permafrost is degrading and soil is permanently water-saturated (C_{sat}), to evaluate the effects of spatial variations within the study site on GHG emissions. Two chambers were operated every day, alternating between chambers second day. The automated chambers were closing themselves for 30 minutes three times a day (7h30, 13h30, 19h30). Manual measurements and independent measurements with a commercial gas chamber were also taken in order to compare the accuracy and precision of the new instrumentation.

Preliminary results show that the new automated system tends to underestimate CO_2 fluxes, but that the measured trends of carbon emissions are similar to the commercial chamber. The greatest CO_2 emissions came from C_{sat}, followed by C_{OTC}, C_n and C_{soil}. Carbon dioxide fluxes from C_{soil} were more than half the emissions of C_n, suggesting that the soil is the main CO_2 emitter.

Research related to transportation infrastructure

Team members, particularly NIs Allard and Fortier, are involved in several major projects that aim at providing a better understanding of the behavioral relationship between transportation infrastructures and the permafrost they are built on. The projects are mainly applied to roads and airports. The team has developed a protocol for an integrated and complete sequence of various types of laboratory analyses. All terrain information is gathered in GIS applications. Integrated information, results and important implications for decision making and for improving engineering designs are thereafter presented and discussed with stakeholders such as regional administrators, engineering designers and construction engineers. In 2014, we were involved principally in four specific projects:

1. The assessment of permafrost conditions and permafrost related processed underneath the Iqaluit airport. This is a continuing project that begun in 2010. Repairs and updates on this major infrastructure were initiated in 2014 and are expected to last three years for a total cost of about $300 M. Our main contributions in 2014 consisted in continued monitoring of thermistor cables installed under various com-

Figure 7. Automated soil respiration chambers in operation in Salluit (photo by Samuel Gagnon).

ponents of the infrastructure (runway, aprons, shoulders, natural terrain) in order to evaluate the impacts of pavement and other surfaces on the ground thermal regime, the inter annual variations of thickness of the active layer and the groundwater regime in the active layer under the infrastructure. Six shallow (down to 4 m deep) holes with core recovery were drilled along the central section of the runway with a portable drill in order to complete the spatial coverage of ground ice conditions mapping because that section could not be drilled with larger machinery in 2013 as the central section of the runway can never be closed to air traffic. Meetings were held on site with the designing engineers and the contractor to help operational problems related to ditching and embankment expansion in summer and to better inform workers on basic engineering practices on permafrost.

2. The Kuujjuaq paved runway is a site of continuous surveys since 2006. The active layer in this region at the southern margin of permafrost distribution now reaches 3 m deep and the permafrost temperatures below are close to 0°C. An impact of this active layer deepening was a change in ground water circulation which now flows under a section of the runway, leading to annual heave and settlement that create damages to the runway and to potential loss of bearing capacity of the pavement during thaw. In 2014 the monitoring of piezometers, water content probes and thermistors was pursued. The data will help

design better drainage works and will support modeling.

3. The Beaver creek test site along the Alaska Highway has been a road-on-permafrost test site for several years. Of particular interest are studies run to monitor how ground thermal regime of the ice-rich permafrost under the road is affected by heat carrying ground water flow, or seepage that carries heat to the infrastructure bed (see above).
4. A study of the airport road in Tasiujaq was done in September 2014 in preparation for its repairs and resurfacing in 2016. Some sections of the road are seriously deteriorated due to thaw settlement. The study was done following the integrated methodology developed at CEN since 2008. Figure 8 shows an example of integrated geocryological and peophysical surveys along the road.

Outreach and Inuit education and training on basic permafrost knowledge and land management issues

It is scientifically and socially important to set up relevant and reliable tools where local populations are involved in the long term monitoring of their environment and, also, to have tools to increase the competence of community members in land management and construction over permafrost terrain. For such initiatives to be sustainable, they have to be driven by local institutions.

Expertise and resources developed in this project contribute to the development of the Avativut Program (Lévesque et al.) http://www.cen.ulaval.ca/Avativut in collaboration with the Kativik School Board (KSB). This program engages students in environmental data collection and archival using scientific protocols. Hands-on Learning and Evaluation Situations (LES) are designed and implemented within the Nunavik Science and Technology Curriculum. Avativut is co-funded by ArcticNet project 2.6 (Henry et al.), this project, by AADNC project "Life on permafrost: Community planning empowerment" and

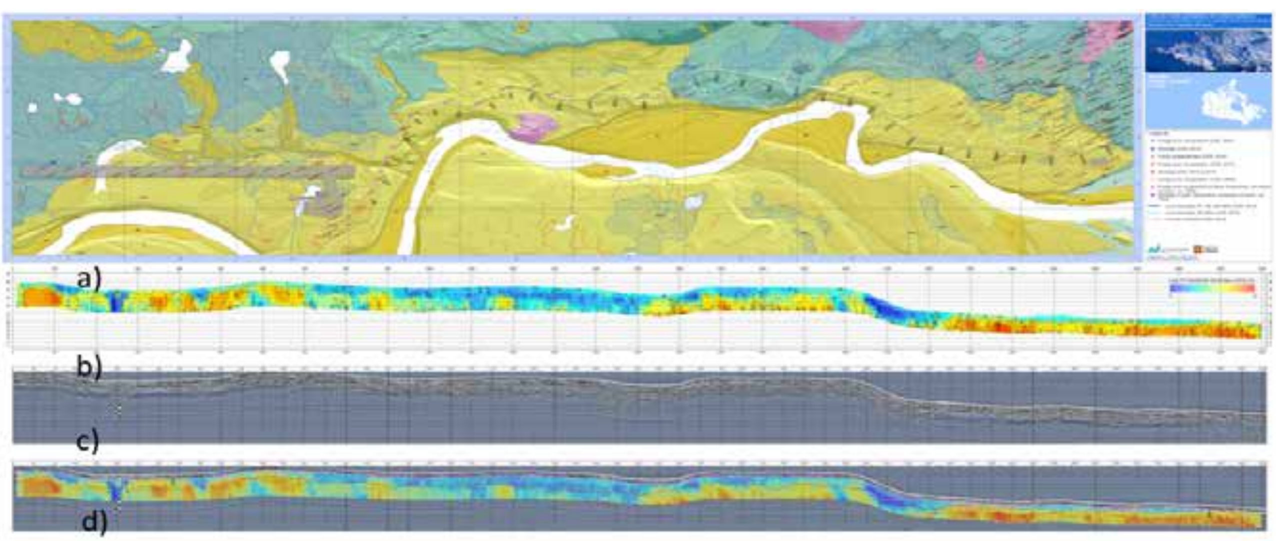

Figure 8. Permafrost characterization along the road to the airport, Tasiujaq, Nunavik. A) surficial geology map with locations of soundings, drillholes and survey pits. B) Capacity resistivity survey profile along the road. c) Ground penetrating radar profile. D) superposition of Resistivity and GPR profiles. (Figure produced by E. L'Hérault and team.)

by the programs NovaScience (Quebec Gov.) and PromoScience (NSERC).

This multisectorial initiative involves members of the Centre d'études nordiques (CEN) from Université du Québec à Trois-Rivières (UQTR), the Institut National de la Recherche Scientifique (INRS Centre Eau Terre Environnement) and Université Laval.

The program objectives are:

1. To set up and secure a long term community-based environmental monitoring program and climate change database;
2. To produce innovative and culturally relevant educational material for Inuit students;
3. To spark interest for environmental sciences, encourage school perseverance and transfer scientific knowledge for capacity-building among Inuit Youth, the future leaders and managers;
4. To bridge science and local knowledge; and
5. To increase awareness to climate change.

Progress was made in 2014-2015 in developing the Permafrost LES. The LES include discussions with Elders and explore Inuktitut related terms.

PermaSim, a computer-based interactive simulation module nearly completed as part of the Permafrost LES and testing with teachers and students has begun in the Kuujjuaq secondary school. When using the animation module that is driven by a conventional mathematical heat transfer model (Tone), the students can observe evolving freeze-thaw cycles of the active layer and temperature cycles in the various soil types driven by air temperatures from their own community (Figure 9). The software allows them to make experiment such as changing snow and vegetation covers. PermaSim was in demonstration at the Arctic Change conference in Ottawa last December. The educational software is also intended to be used for training staff in local governments and communities. It can also be valuable for training university students.

DISCUSSION

Destabilization of massive ground ice and ice wedges more and more appear as an extremely important terrain issue in the continuous permafrost zone of northern Canada. However, under climates that are still very cold despite current warming, new permafrost aggrades in depressed furrows over thawed or eroded ice wedges and in landslide scars. A new state of terrain equilibrium, albeit likely a transitional one, is being set. The High Canadian Arctic also has vast extents of very cold environments where biogeochemical processes are still very poorly understood, such as water tracks and solifluction lobes and stripes.

Ground surface warming and deeper active layer provide for ecosystem respiration from carbon that was previously stored in the permafrost and increase the rate of biogeochemical cycling of elements and the primary productivity. The scale of spatial variability of tundra respiration is beyond the capability of representation of climate models. Therefore, as demonstrated by field measurements in the Salluit detailed study, it appears that global model outputs will remain very uncertain before the drivers of biogeogeochemical processes are better understood and before better soil maps of Northern Canada are produced. The same can be said of carbon releases from the permafrost given the widespread terrain heterogeneities over the global landscapes.

Thermokarst in the discontinuous permafrost zone leads ultimately to increased organic matter storage in soil horizons when the long term sequence of shrub and tree growth in thermokarst hollows is included in the overall sequence of ecosystem changes as revealed by interdisciplinary research coupling geomorphological and ecological processes such as was done in the Umiujaq region. Many thermokarst lakes are likely to change ultimately from methane generators to carbon reservoirs as they drain or get invaded by peatlands and vegetation.

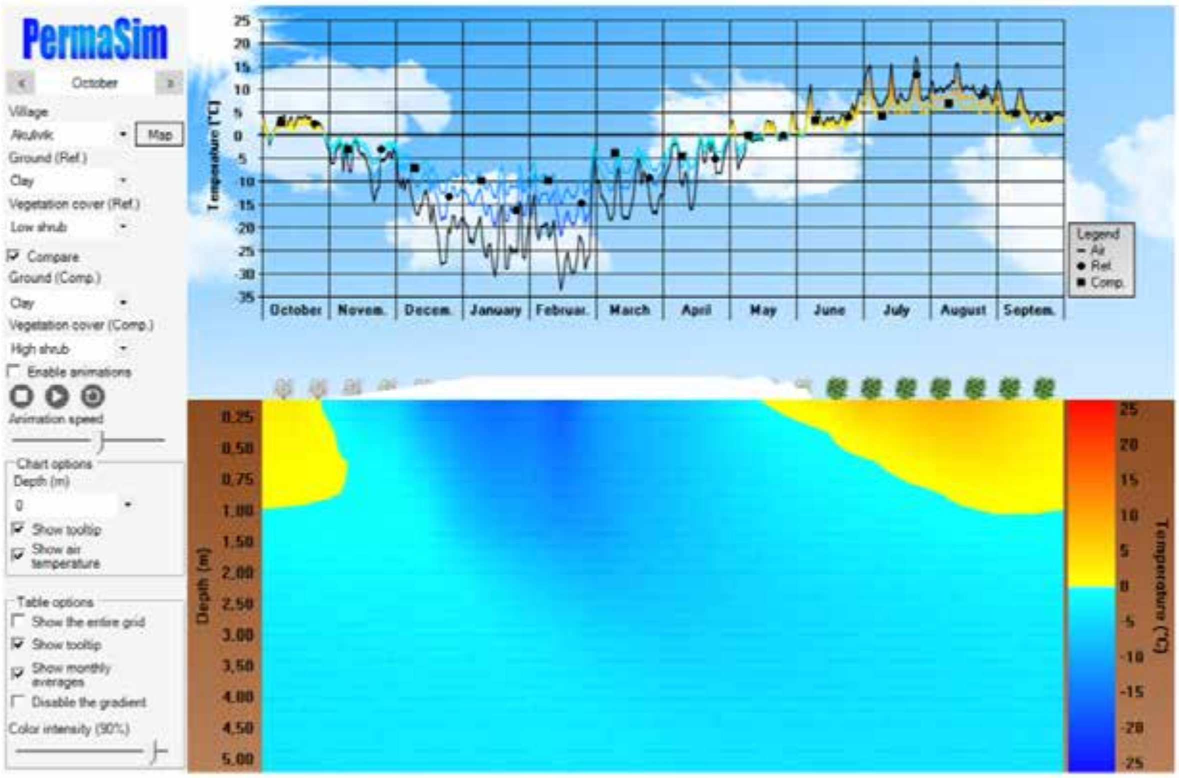

Figure 9. Example of a dsplay of PermaSim. Upper graph, annual air temperature curve (black) and two potential soil surface temperature curves depending on snow cover thickness selected by the student. Lower graph, annual evolution of the ground temperature profile. The simulation is animated on the computer screen.

The need for better permafrost characterization under actual and new infrastructure is increasing. More local and basic knowledge on permafrost and degradation processes are necessary to develop protection and rehabilitation strategies.

CONCLUSION

The project ends the third ArcticNet funding cycle on a comprehensive vision of emerging permafrost related issues of Arctic wide significance, particularly as ground ice amounts and ecological changes are concerned. Education and training material for the Inuit is being produced. Contributions to technology, some unique so far to our group (CT-Scan, laboratory techniques, DTS) are in progress and already applied in science, in community work and in infrastructure research.

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. Community permafrost mapping and reporting is taking more importance and is in demand. The impetus of the research shall be on those applied matters for the next and final funding cycle of ArcticNet.

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Most of all, the project would not be possible without close collaboration with a large number of Inuit in a large number of communities.

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EFFECTS OF CLIMATE CHANGE ON THE CANADIAN ARCTIC WILDLIFE

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Influence of climatic fluctuations on Common Eider life history and population dynamics: variation within and between populations
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Influence of Allostatic Load on Reproductive Decisions and Fitness in a Long-Lived Seabird
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The emergence of avian cholera and its role in regulating northern common eider populations in the eastern Canadian Arctic
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Écologie alimentaire des grands prédateurs terrestres arctiques: loup arctique, carcajou, grizzly
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
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Utilisation de l´espace et mouvements hivernaux chez un prédateur de la toundra, le Harfang des neiges
Barry Robinson, Doctoral Student (University of Alberta)
On the Breeding Behavior and Foraging Ecology of Arctic Peregrine Falcons (Falco Peregrinus Tundrus)
Andréanne Beardsell, Masters Student (Université Laval)
Catherine Doucet, Masters Student (Université du Québec à Rimouski)
Phénologie de la reproduction et disponibilité des ressources alimentaires pour les bruants lapons dans un contexte de changements climatiques
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
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Vulnerability of arctic fox (Vulpes lagopus) dens to climate change in the Canadian High Arctic
Vincent Marmillot, Masters Student (Université Laval)
Effects of environmental conditions on the Greater Snow Goose molt (Chen caerulescens atlantica)
Camille Morin, Masters Student (Université du Québec à Rimouski)
Facteurs déterminant la taille de portée du renard arctique à l'ile Bylot, Nunavut
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
Guillaume Slevan-Tremblay, Masters Student (Université Laval)
Effets de la prédation sur le broutement des lemmings dans l'Arctique canadien
Graham Sorensen, Masters Student (University of Windsor)
Mikaël Jaffré, Post-Doctoral Fellow (Université du Québec à Rimouski)
Pierre Legagneux, Post-Doctoral Fellow (Université Laval)
Amie Black, Technical Staff (Environment Canada)
Elise Bolduc, Technical Staff (Université du Québec à Rimouski)
Marie-Christine Cadieux, Technical Staff (Université Laval)
Nicolas Casajus, Technical Staff (Université du Québec à Rimouski)
Frédéric Dulude-de-Broin, Technical Staff (Université du Québec à Rimouski)
Michael Janssen, Technical Staff (Environment Canada - Science and Technology Branch)
Don-Jean Léandri, Technical Staff (Université Laval)
Christie Macdonald, Technical Staff (Environment Canada)
Pascal Pettigrew, Technical Staff (University of Alberta - Department of Renewable Ressources)
Mark Prostor, Technical Staff (University of Alberta)
Gabrielle Robineau-Charette, Technical Staff (Arctic Raptors Inc.)
Denis Sarrazin, Technical Staff (Centre d'études nordiques)
Fanny Sennez-Gagnon, Technical Staff (Université Laval)
Mathieu Tetreault, Technical Staff (Université de Sherbrooke)
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Northern HQP

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ABSTRACT

Many northern ecosystems are undergoing major shifts related to climate change. This adds to increasing pressures due to resource development. An understanding of these transformations and of the significance of their consequences is critical to anticipating ways in which potential negative and positive effects to wildlife populations (and ultimately humans) may be mitigated or used through sound management. Our overall goal is to provide the wildlife-related knowledge necessary to conduct the integrated regional impact studies of the 'Eastern Arctic' and 'Hudson Bay', two of the four regions identified by ArcticNet to conduct regional impact studies. In addition, we contribute to all international efforts synthesizing knowledge on biodiversity for the benefit of northern populations and policy makers. We work through 5 specific objectives. First, we identify the main vulnerabilities of Arctic wildlife with regards to climate change and resource development. Second, we monitor more than 30 wildlife populations (mostly tundra wildlife and marine birds) at study sites located in the Eastern Canadian Arctic (e.g., Belcher Islands, Rankin Inlet, Coats Island, East Bay-Southampton Island, Digges Island, Deception Bay, Bylot Island, St.Helena Island). Third, we develop models to better understand the key interactions between species that drive the tundra food web. Fourth, we use data from our field work and from the literature to analyze past and present responses of wildlife to climatic variability in order to develop Impact Models. Finally, we project some wildlife patterns into the future by forcing these Impact Models with regional climate change scenarios. This project is a collaboration between ArcticNet researchers and a number of partners including the Canadian Wildlife Service (Environment Canada), Parks Canada Agency, Wildlife Conservation Society Canada, Nunavut Tunngavik Inc., Nunavut Wildlife Management Board, Baffinland Iron Mine Corporation, Department of Environment of Government of Nunavut, Nunavut General Monitoring Program, and many Northern communities, especially members of their Hunting and Trapping Organizations.

KEY MESSAGES

- Monitoring a set of key wildlife species is required to assess ecosystem changes taking place in the Arctic, whether they are caused by climatic variation or natural resources development.
- This project monitors more than 30 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 Arctic Biodiversity Assessment and the Circumpolar Biodiversity Monitoring Program.
- In addition, this project tests 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 lots of new knowledge about the role of sea ice in wildlife ecology.
- 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 (e.g. Peary caribou, polar bear, arctic fox, snowy owl) 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 this may change quickly.
- As the abundance of some species will increase while others will decrease, we expect important shifts in wildlife species assemblage and that this will vary longitudinally.
- 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.
- 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 arctic human communities depend on the composition and health of ecosystems. Therefore, assessing the vulnerabilities of ecosystems and wildlife is needed to assess the vulnerability of human communities.

OBJECTIVES

We continued to pursue the objectives identified in 2012, at the start of our ArcticNet Phase III project:

1. to identify the main vulnerabilities of Arctic wildlife with regards to climate change;
2. to pursue and enhance the wildlife monitoring program forming the core of this project;
3. to develop trophic interaction models to better understand key interactions driving the tundra food web;
4. to develop Impact Models describing selected responses of Arctic wildlife to climate change;
5. to force these Impact Models with regional climate change scenarios.

INTRODUCTION

Our project had been carefully introduced in our 2013-2014 report, and its context remains unchanged. The following thus largely repeats the introduction provided last year.

The increase in Arctic surface temperatures over the last decades and the increased development of natural resources in northern regions have generated major concerns about the future of Arctic wildlife, traditional hunting activities, and the integrity of arctic ecosystems. Effects of climate change on the timing of biological events (phenology of species), the distribution of species, and the food webs (trophic dynamics) of wildlife communities are now apparent. Effects of mining sites and mineral shipping routes on wildlife are anticipated. Yet, as Arctic climate continues to warm and the pace of development increases, our capacity to measure and predict the responses of biological systems and their cascading effects through food webs, and ultimately their effects on humans, remains limited. We need baseline data on natural systems. We are also faced with complex interactions between wildlife species and between ecosystems and humans. The mandate of this project is to better understand the current and anticipated effects of climate change and natural resource development on Arctic wildlife.

Wildlife species are sentinels of environmental change and the first effects of climate change on species can be detected in the timing of biological events (their phenology; Berteaux et al. 2004). We monitor the phenology of many populations, such as eider ducks and greater snow geese, which are significant to the Inuit and for which extensive data sets already exist. We also monitor the phenology of long distance migrants like shorebirds and raptors, as they form an important component of the arctic biodiversity. The movement of wildlife over the land, sea and sea ice is another important component of wildlife ecology that responds quickly to changing environmental conditions (CAFF 2013).

The northward progression of isotherms in the Arctic will have wide-ranging impacts on the distribution of wildlife, with cascading effects on the functioning of ecosystems. Many arctic species may undergo population declines in response to warming not because they cannot tolerate more benign environmental conditions, but because they will be out-competed in these new environments by southern invaders with less tolerance for harsh conditions but better growth potential under more benign conditions. Invading species come from the southern boundary of the Arctic and can sometimes move fast to more northerly locations. For example red foxes have invaded Baffin Island and are now found in southern Ellesmere Island.

Climate imposes a rough structure to wildlife communities through its effects on plant growth (primary productivity). However, the interactions between plants, herbivores, and predators (the food web dynamics) shape the fine-scale structure of communities (Legagneux et al. 2012, 2014). We need to know how the relative influences of climate and biotic factors vary geographically, to better anticipate where the effects of climate change on the functioning of the tundra will be greatest. We study the interactions between plants, herbivores, and predators at several sites, such as Bylot Island, Rankin Inlet, and Southampton Island to better understand climatic impacts on the food web dynamic. We also investigate how seabirds and several other species are influenced by sea ice and potential mineral shipping routes, as this is a poorly understood aspect of their ecology.

ACTIVITIES

<u>Time frame and study area:</u> Field work was carried out from May-August 2014 at East Bay (Southampton Island), Rankin Inlet, Mary River (Milne Inlet to Steensby Inlet), Digges Island, Coats Island, and Bylot Island. Boat-based bird and polar bear research was carried out in July 2014 along the south coast of Hudson Strait in Digges Sound, in partnership with the community of Ivujivik. Electronic equipment allowed us to collect climatic and biological data throughout the year.

<u>Research:</u> Intensive field work was done and detailed analyses of collected data (capture and marking of wildlife, nest abundance, nest survival, digital pictures, locations of animals and movement behavior, avian distance sampling, avian disease sampling) and samples (tissues from wolf and wolverine carcasses,

lemming winter nests, bird of prey pellets, plant above-ground biomass, insects and spiders, wildlife blood, and hairs/feathers) were performed. In addition, 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.
- Retrieval of annual snow condition data from one automated environmental monitoring station on Bylot Island.

Plants

- Monitoring of plant primary production and goose grazing impact in wetland habitats at Bylot Island (24 exclosures).

Arthropods

- Monitoring of insect and spider emergence and diversity using pitfall traps (1000 samples collected over the summer).

Birds (raptors)

- Monitoring of ca. 450 peregrine falcon, gyrfalcon and rough legged hawk nest sites at Rankin Inlet and Mary River (Milne Inlet to Steensby Inlet).
- Monitoring of peregrine yearly movements using 70 Lotek geolocators (deployment completed, recovery in progress, 14 recovered to date).
- Monitoring of chick growth rate from 70 raptor nests.
- Detailed observation of peregrine behavior, breeding phenology, causes of mortality and identification of marked birds using infrared-triggered cameras and direct observation.
- Banding of ca. 120 peregrine falcons and rough-legged hawks at Rankin Inlet and Mary River.
- Monitoring of the reproductive activity of 98 nests of snowy owls, 31 nests of rough-legged hawks (among 78 known potential nesting sites visited), 6 nests of peregrine falcons (among 10 known potential nesting sites visited), and 1 nest of gyrfalcon at Bylot Island.
- Capture and marking of 8 adult female snowy owls with satellite transmitters at Bylot Island.

Birds (shorebirds and passerines)

- Monitoring of ca. 100 shorebird nests and 82 passerine nests at Bylot Island.
- Monitoring of chick growth rate from ca. 40 passerine nests (ca. 100 chicks) at Bylot Island.
- Marking of ca. 50 shorebirds and ca. 150 passerines at Bylot Island.
- Deployment of 54 geolocators on shorebirds (42 on American golden-plovers and 12 on common-ringed plovers) and recovery of previously deployed geolocators from six American golden-plovers on Bylot Island.
- Monitoring of body condition and stress levels in peregrine falcons through collection of 23 three-minute post-capture and 23 thirty-minute post-capture blood samples for analysis of corticosterone, triglycerides, and B-hydroxybuterate.
- Monitoring of predation rates of shorebird nests using time-lapse photography at Southampton Island (5 cameras) and Coats Island (5 cameras).
- Monitoring of 72 nests of 6 species of shorebirds on Southampton Island to better understand potential mechanisms of population decline among shorebirds in this region.
- Monitoring of the growth rate of 75 known-aged snow bunting chicks from 19 nests on Southampton Island.

Birds (geese and seabirds)

- Monitoring of reproductive activity of 491 nests of snow geese at Bylot Island.
- Monitoring of the habitat use of eider duck flocks by conducting snowmobile surveys, and comparison of their distribution with previous years (Inuit field workers were trained to continue this work without our direct participation).
- Monitoring of the reproductive activity of 77 nests of long-tailed jaegers, 5 nests of parasitic jaegers, and 41 nests of glaucous gulls at Bylot Island.
- Capture and banding of 27 long-tailed jaegers and marking of 20 individuals with geolocators at Bylot Island to track annual movements.
- 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 2001 snow geese with leg bands, including 203 adult females with neck-collars, at Bylot Island to monitor the impact of harvest and climatic factors on 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.
- Monitoring of 13 nests of Sabine's gulls on Southampton Island.
- Surveying of common eider breeding colonies in Digges Sound (Nunavut) to evaluate the severity and geographic scope of avian cholera and polar bear nest predation on eider reproduction.
- GPS tracking of 68 thick-billed murres from Digges Island to establish key marine habitat areas during the breeding season.

Mammals

- Monitoring of 114 fox dens at Bylot Island.
- Monitoring of 28 arctic fox yearly movements in the eastern High Arctic using Argos satellite transmitters.
- Monitoring of long-range movements (up to 2000 km) of arctic foxes across Nunavut.
- Monitoring of lemming abundance and demography using various methods (395 winter nests sampled; live-trapping of 477 brown lemmings and 40 collared lemmings during ca. 3000 trapping days; snap-trapping of 26 brown lemmings and 4 collared lemmings during ca. 2100 trapping-days; counts of burrows and feces at 192 pairs of 60 m-transects) at Bylot Island.
- Monitoring of lemming abundance at Rankin Inlet (snap trapping: 500 trapping days), and north Baffin Island (live trapping: 300 trapping days).
- Collections of 123 fecal samples of brown lemmings to monitor stress level through analysis of corticosterone on Bylot Island.
- Monitoring of 21 ermine dens and 50 shelter boxes at Bylot Island.
- Detailed observation of fox behaviour on Bylot Island using 50 infrared-triggered cameras and direct observation.
- Determination of diet of 98 wolverines and 81 wolves by analysing stomach contents of animals harvested in Nunavut during hunting season of 2012-2013.

- Detailed observation of nest predator (e.g. polar bear, arctic fox) behaviour using infrared-triggered cameras and direct observation.

Syntheses

- Synthesis across several circumpolar study sites of climatic and ecological factors structuring tundra ecosystems.
- Modelling of ecosystem trophic structure at one of our tundra study sites (Bylot).
- Participation to the implementation of the Circumpolar Biodiversity Monitoring Program coordinated by the Conservation of the Arctic Flora and Fauna initiative.
- Creation 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.

RESULTS

The year 2014-2015 was particularly productive, with many new results emerging from our long-term monitoring, field experiments, and data synthesis efforts. We summarize six representative new findings, all in direct line with our project objectives. The first two findings illustrate scientific progress rooted in our wildlife monitoring, the three following ones show how the development of wildlife tracking technology generates important new ecological understanding, and the last finding stems from our efforts to synthesize collected data across large spatial scales. Methodological details and statistical treatment of data can be found in specialized reports and refereed publications.

Black fly depredation in peregrine falcons

We monitor breeding sites of many wildlife species (peregrine falcon, snowy owl, arctic fox, shorebirds, etc.) using automatic infrared cameras. Millions of pictures are recorded every summer, yielding highly valuable biological information, as demonstrated by the example below.

A breeding pair of peregrine falcons was observed at a regularly monitored nest site near Rankin Inlet. Four eggs hatched on 12 and 13 July 2013, and nestlings were brooded normally. On 20 July, several flies could be seen on the down of the nestlings by 18:41 (Figure 1a). Despite being covered by the adult female, the chicks exhibited loss of down in small patches by 19:45, and well-demarcated bloodied, skin lesions were obvious by 20:24 (Figure 1b). During the next two hours, nestlings exhibited large denuded patches, clearly exposing severely inflamed cutaneous tissue underneath the down (Figure 1c). By 03:58 the next morning, all nestlings had died and carcasses had been removed from the nest by the female.

Inspection of images recorded at nine other breeding sites revealed that broods at eight sites suffered some degree of black fly infestation. In total, six broods from 10 sites monitored with cameras were reduced partially or completely resulting in the death of 13 of 35 (37%) nestlings because of the cumulative effects of black fly harassment.

Origin of red fox invading the Canadian Arctic

The red fox expanded its distribution over large parts of the Canadian Arctic during the 20th century. Our wildlife monitoring has previously shown that red foxes breed on Herschel Island and Bylot Island, where they now compete with arctic foxes for food and dens. One unresolved question was the origin of these red foxes. Some authors proposed that the European red fox, introduced in Eastern North America during

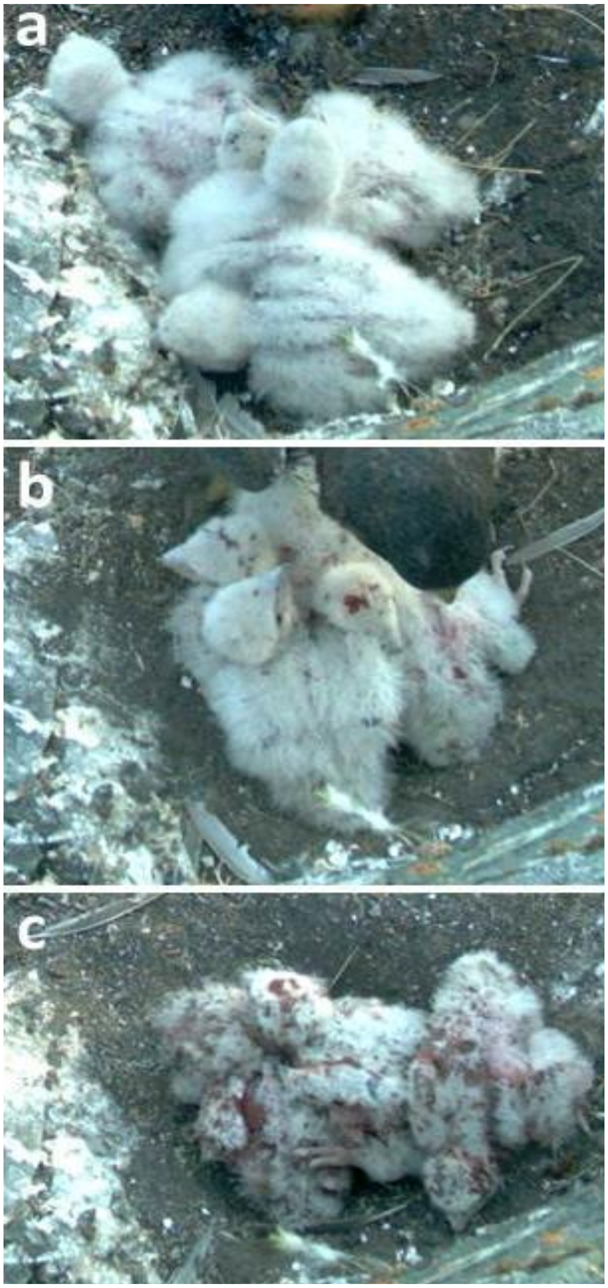

Figure 1. Sequence of images showing the result of black fly harassment on peregrine falcon nestlings at Rankin Inlet, 20 July 2013. a) 18:41: several flies are seen on the down of the nestlings. b) 19:45: chicks exhibit loss of down in small patches. c) 20:24: well-demarcated skin lesions are observed. All nestlings had died by 03:58 the next morning (photo credit: Alastair Franke and Vincent Lamarre).

the 18th century, may have spread and caused the species' expansion in the Arctic. Assessing the origin of red foxes in the Canadian Arctic was critical to determine whether their presence constitutes a case of an invading exotic species.

We analyzed genetic samples obtained from Herschel and Bylot. We identified DNA segments from both locations that were divergent from those in Eurasia, but shared with neighboring indigenous North American populations (Figure 2). Thus the 20th century expansion of red foxes in the Canadian Arctic involved nearby populations potentially benefiting from habitat changes, rather than an exotic species invading new habitats.

Study of wildlife movements: seabirds

Recent increases in resource development activities are projected to increase shipping traffic in Canada's Eastern Arctic marine regions. However, there is not enough information to properly assess potential ecological impacts of year-round shipping lanes on marine wildlife. Our research seeks to determine the distribution and abundance patterns of seabirds, and to identify their use of key marine habitats.

In 2014, we tracked thick-billed murres at sea in both the low and high Arctic, namely at Prince Leopold Island, Cape Graham Moore, Bylot Island, and Digges Island. At the Digges Island colony we also investigated whether birds breeding at a variety of locations within the colony utilized different marine habitat areas, and whether this changed between breeding stages (i.e. incubating eggs vs feeding chicks).

Murres from Cape Wolstenhome tended to use the marine area North and East of Digges Island while Murres from Digges Island tended to spend more time in the area South and West of the Island. Our data also suggest some partitioning of marine resources between murres located within different regions on the Digges Island colony itself (Figure 3).

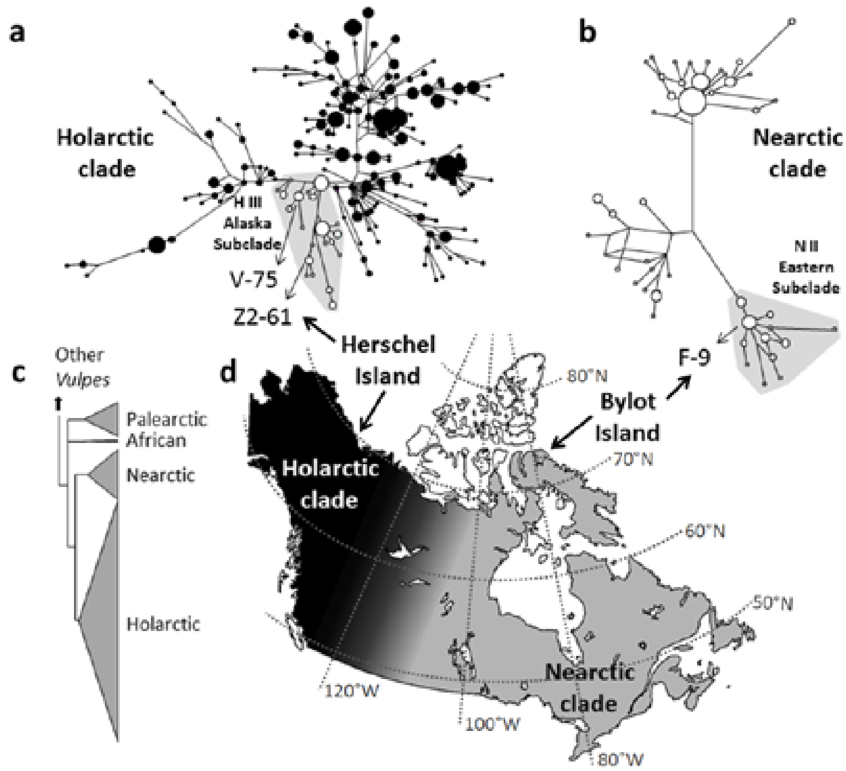

Figure 2. The genetic classification of red foxes shows that individuals from Herschel and Bylot belong to the Holarctic (a) and Nearctic (b) clades, respectively. Both clades characterize North American red foxes and differ from European red foxes (Palearctic clade, c). The red fox distribution map (d) shows the approximate geographic distribution of the two lineages of North American red foxes. From Berteaux et al. 2015. © 2015 Springer-Verlag Berlin Heidelberg.

Study of wildlife movements: snowy owls

We examined the spring (March to June) and annual movements of snowy owls by tracking 9 adult females in the Canadian Arctic for up to 3 years with satellite transmitters. Females generally settled in far apart areas to breed every summer across the eastern Arctic (Figure 4). Individual breeding dispersal distance between consecutive years averaged 725 km (range 18 to 2224), among the largest values recorded for any bird species. Tracked owls displayed searching movements for extended periods (up to 108 days) and travelled over large distances (up to 4093 km) each spring before settling in areas where lemming abundance was high.

Our results show that owls are very efficient in tracking lemming abundance over large areas and in finding suitable breeding areas every year. They also indicate that owls of eastern Nunavut and Nunavik likely belong to the same population.

Study of wildlife movements: effects on spread of avian cholera

Avian cholera is one of the most lethal diseases for birds in North America. Although it has circulated in southern Canada and the United States for many years, its emergence among eider ducks in the North is new. We compared common eider migration pathways generated from our satellite tracking data to known

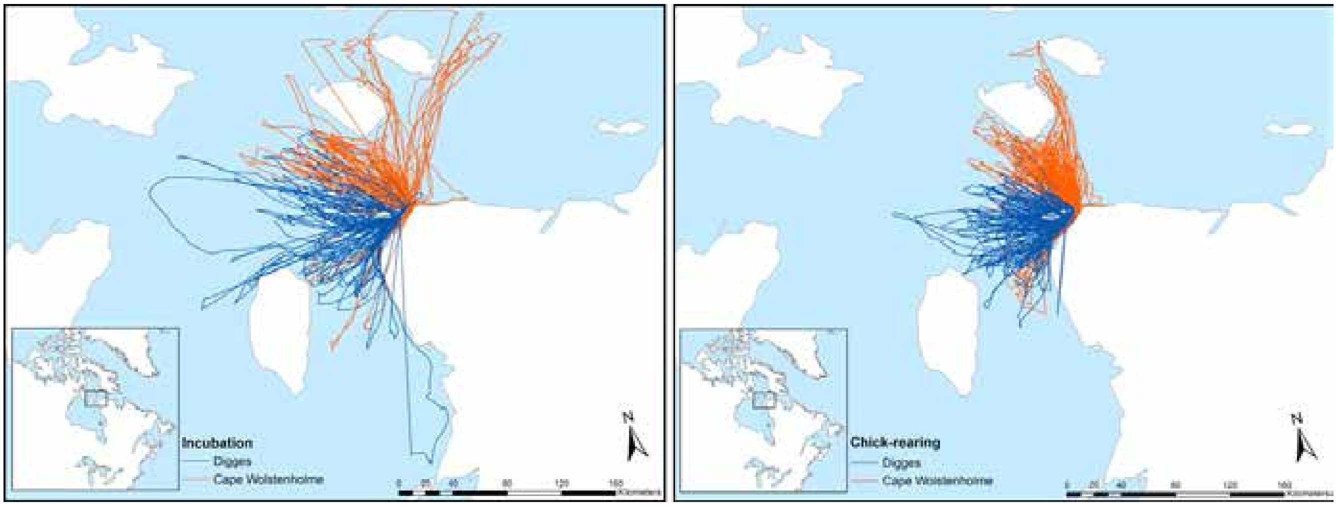

Figure 3. GPS tracks of breeding thick-billed murres (summer 2014) show evidence for colony partitioning of foraging areas in Digges Sound. Foraging flights of murres nesting in the Cape Wolstenhome colony and nearby Digges Island colony are shown in orange and blue, respectively. Note how foraging range decreases between egg incubation (left map) and chick-rearing (right map) periods.

avian cholera outbreaks to investigate potential sources of this disease.

The eider satellite tracking data suggest that eiders wintering in Atlantic Canada typically use the southern coast of Hudson Strait during spring migration, which corresponds to the distribution of known avian cholera outbreaks (Figure 5a). The distribution of outbreaks and the comparisons with migration patterns of common eiders wintering in west Greenland (Figure 5b), and migration patterns of mid-continent lesser snow geese (Figure 5c), suggest that the disease is spread by eiders wintering in Canada through contact with Atlantic eider populations, where the disease is known to circulate in the Gulf of St. Lawrence.

Structure and functioning of the tundra food web

We integrated data from our long-term monitoring of Bylot Island with similar data collected across the circumpolar Arctic during the International Polar Year (2007-2010) to analyze factors structuring tundra food webs. We found that air temperature was strongly

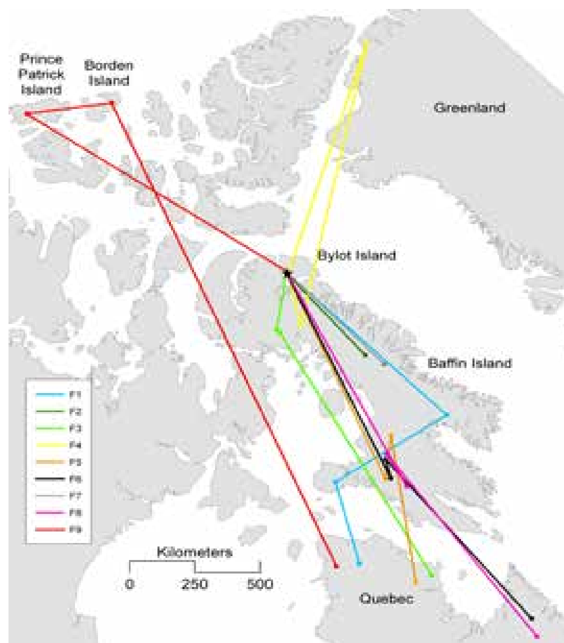

Figure 4. Breeding site locations (dots) of nine adult female snowy owls originally marked on Bylot Island (star) and tracked with satellite transmitters over four consecutive breeding seasons (2007 – 2010). Breeding sites are chronologically displayed and linked by a line for each individual. From Therrien et al. 2014a. © 2014, John Wiley and Sons. © 2014 Therrien, Gauthier, Pinaud, Bêty.

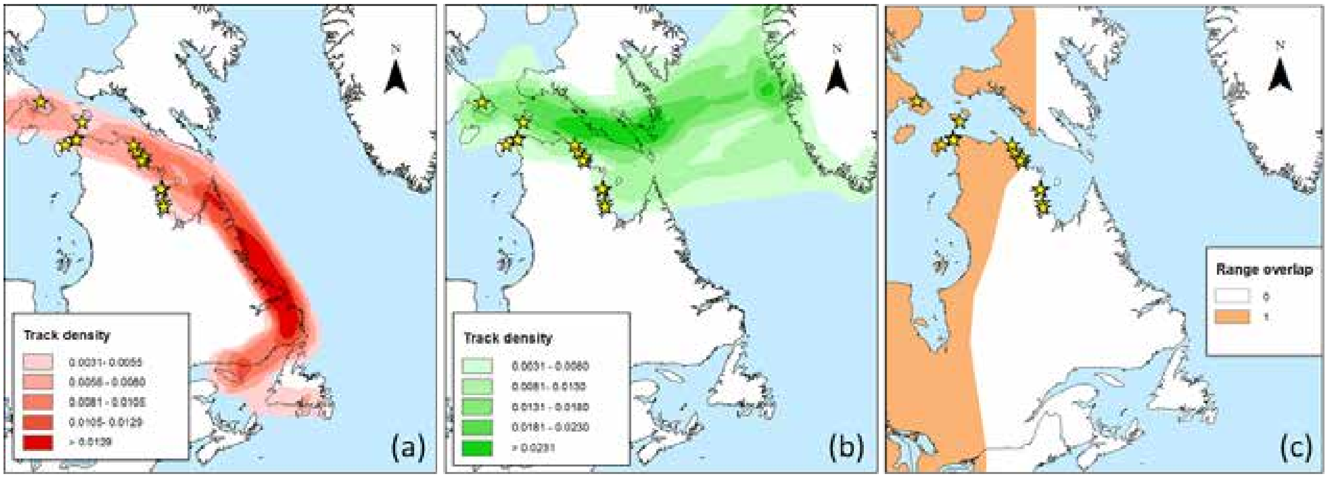

Figure 5. Avian cholera emergence pattern in Hudson Strait (yellow stars) in relation to the migratory paths of (a) common eiders wintering in Atlantic Canada, (b) common eiders wintering in west Greenland, and (c) mid-continent lesser snow geese.

correlated with the strength of food web interactions: predation on small herbivores (lemmings, voles and ptarmigan) intensified at warmer sites in conjunction with reduced consumption of annual plant growth (Figure 6).

Overall, predator-prey interactions were a more important interaction of the tundra food web than herbivore-plant interactions, except in the High Arctic where plant productivity is lower and the food chain is more simple than at lower Arctic latitudes. Another key result was that predation intensity varied according to the body size of herbivores in the ecosystem, with large herbivores (caribou and muskoxen) mostly escaping strong limitation by predators under natural conditions.

DISCUSSION

Black fly depredation in peregrine falcons

Previous studies in which black flies had negative effects on raptor nestlings occurred where the distribution of raptors and flies overlap (e.g., Smith et al. 1998). However, ornithophilic black flies (flies feeding on birds) have not typically been found at Rankin Inlet (D.C. Currie, pers. comm. 2014). However, some species known to select avian hosts have been found during inventories conducted south of our study area near Arviat, and west of Rankin Inlet along the Thelon River (Adler et al. 2004). It is thus possible that our results signal a range shift in the region, as expected with climate change (Root et al. 2003, Williams and Liebhold 2002).

Evidence suggests that the distribution of some arthropod species has shifted northward in response to climate change (Parmesan et al. 1999, Musolin 2007) and some parasites are expanding their distribution range in Canada (Kutz et al. 2013). However, the single occurrence we observed could also be a normal, albeit rarely occurring, event due to the combination of optimal climatic conditions for the reproduction of adult flies during the previous summer and the development of immature stages in running water. Ongoing annual monitoring is required to determine whether ornithophilic black flies are to become a regular challenge for birds in the Arctic as a consequence of climate change.

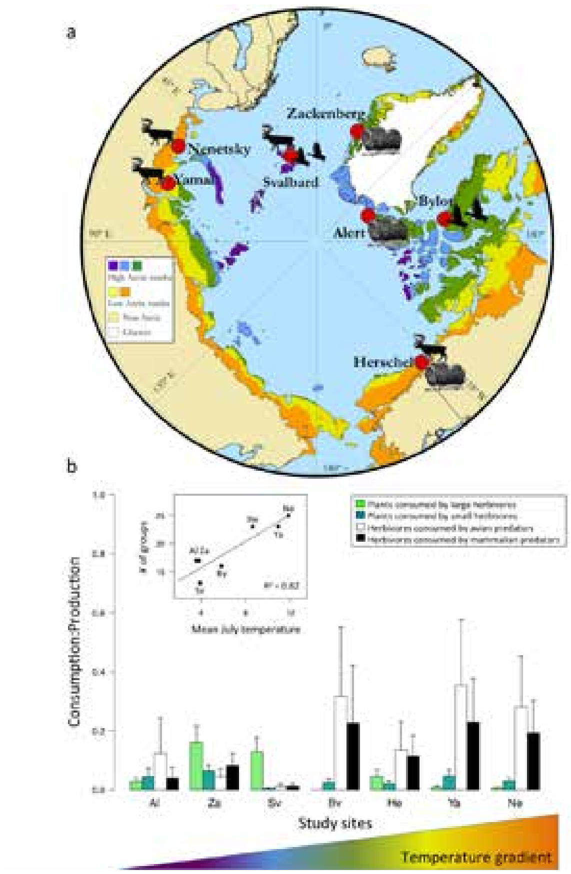

Figure 6. The seven Arctic tundra study sites are identified by red dots on a map of bioclimatic zones from high to low Arctic tundra (a). The pictograms represent the most abundant herbivores at each site. The median consumption rates (consumption:production ratios) at each study site are shown in (b). Consumption rates of plants were divided according to the size of herbivores consuming them (green/blue bars), and consumption rates of herbivores were divided according to the predator types (white/black bars). Sites are ranked in increasing order of average July air temperature. The insert graph shows that the number of species (or groups of species) increased with air temperature. From Legagneux et al. 2014. © 2014, Springer Nature.

Origin of red fox invading the Canadian Arctic

Archeological evidence supports the interpretation that red foxes in the Canadian Arctic are native in origin, as the red fox was present several centuries ago in the Yukon North Slope (Nagy 1988) and 2000 years ago in northern Quebec (Monchot and Gendron 2011). Our results contradict the hypothesis that red foxes of exotic origin were involved in the 20th century expansion of red fox into the Arctic (Kamler and Ballard 2002). This hypothesis relied heavily on interpretations about changes in frequencies of color phenotypes. We doubt that fur color can be used reliably to indicate population of origin because there was considerable spatial and temporal variability in fur color within North American red foxes (Merriam 1900, Butler 1951).

Resolving the origin of red foxes in northen Canada was important. First, differences in tolerance and aggressiveness between red fox forms might exist, with implications on the future outcome of competition between red and arctic foxes in the Arctic. Second, management decisions regarding expanding populations of red foxes could drastically differ according to whether they are of native (North American) or exotic (European) origin.

Study of wildlife movements: seabirds

Our ongoing work is establishing a baseline of marine habitat use from which potential future impacts of resource development to marine birds may be assessed. In particular, our results from Digges Sound in 2014 suggest that any scientific program designed to establish and monitor the key marine habitat areas for breeding colonies of thick-billed murres will need to assess habitat use throughout the breeding season from multiple locations within each colony (Figure 7).

Study of wildlife movements: snowy owls

The high mobility of female snowy owls allows these diet specialists to behave as irruptive migrants and to sustain their reproductive activities during consecutive years even under highly fluctuating resources. Avian predators inhabiting the tundra such as the snowy owl

Figure 7. A thick-billed murre colony in the Eastern Canadian Arctic, as seen from the top of the cliff. Thick-billed murres are one of the most abundant seabirds of the Canadian Arctic (photo credit: Travis White).

can consume large quantities of lemmings and their summer consumption rates can sometimes exceed the maximum growth rate of lemming populations, thereby potentially limiting their growth in a top-down manner (Gilg et al. 2003, Therrien et al. 2014b).

Our study provides evidence that the snowy owl can explore large expanses of the tundra every spring to find areas of high lemming abundance and settle in those areas to produce chicks (Figure 8) without any time-lag, even if this entails net linear movement of more than 1000 km between breeding sites in consecutive years. Such large-scale irruptive movements, combined with the high consumption rates of snowy owls, can promote synchronization among fluctuating small mammal populations over a wide area (Norrdahl and Korpimäki 1996, Ims and Andreassen 2000, Krebs et al. 2002). Predation by this irruptive migrant could therefore have a dampening effect on the amplitude of lemming population cycles over a broad continental scale. This suggests that the snowy owl may play a major role in the tundra food web structure and functioning.

Figure 8. Snowy owl chick (photo credit: Andréanne Beardsell).

Study of wildlife movements: effects on avian cholera circulation

The presence of avian cholera in Canada's Arctic is new and its sources were previously unknown. We have found evidence that cholera has been transferred to northern eider colonies by migratory individuals that have contact with Atlantic eider populations where the disease is known to occur in the Gulf of St. Lawrence.

Structure and functioning of the tundra food web

Our synthesis of data across several arctic terrestrial ecosystems revealed a strong relationship between temperature and ratios of consumption to production across trophic levels (Legagneux et al. 2014). They shed some light on the long-standing debate of top-down versus bottom-up control of arctic ecosystems (Oksanen et al. 2008, 2009, Gauthier et al. 2009). The main differences among our study sites, besides latitude and temperature, were their predator-prey biomass ratios and body size distributions within and across trophic levels. Overall, we found that in the tundra biome, the strength of predation and herbivory is modulated by summer temperature and body size.

Specifically, large herbivores (Figure 9) seem to be mainly limited by primary production as the top-down control by predators weakens considerably with increasing herbivore body size, probably because large herbivores can escape predation to some extent. As the

Figure 9. Large herbivores, such as these muskoxen, are mainly limited by food availability in the Arctic, whereas smaller herbivores, such as lemmings, may be mostly limited by their predators (photo credit: Vincent L'Hérault).

distribution of herbivore body size was independent of temperature in our dataset, an increase in predation pressure on small herbivores was responsible for the strengthening of the predator-prey interaction with temperature.

We thus suggest that the influence of temperature on ecosystem functioning is mediated by predation and that the most significant effects of the current warming of the Arctic on the tundra biome will be indirect. There is also a potential for climate warming to cause a switch from bottom-up to top-down regulation of herbivores at the most northern sites.

CONCLUSION

The Arctic Biodiversity Assessment (CAFF 2013) was a major report endorsed by the Arctic Council to provide policy makers and conservation managers with a synthesis of the best available scientific and traditional knowledge regarding the status and trends of Arctic wildlife. It demonstrated very well how the Inuit population, the international scientific community, and the public in general are concerned about the future of Arctic wildlife. Among these sources of concern are the effects of climate change and rapid resource development.

It is crucial to continue supplying monitoring information on wildlife populations of the Arctic, and on the functioning of arctic ecosystems. This report illustrates, through a few examples, how field monitoring and structured research allow detection and understanding of new trends in Arctic biodiversity. It is also important to research the mechanisms linking ecosystems to drivers of change, and to attempt to predict the future trajectories of arctic biodiversity. Moreover, research is critical to identify the best ways to manage wildlife populations and protected areas, at a time of changing environmental conditions.

In this project, we generate some baseline information on more than 30 wildlife populations spread over a gradient ranging from the Low to the High Eastern Canadian Arctic. We also produce critical information on the functioning of ecosystems and its links with climatic variation. Our results are obtained through efficient collaborations and are transmitted to most governmental and non-governmental organizations active in the field of wildlife and ecosystem research and management in the Canadian Arctic.

As in previous years, numerous northerners took part in our research activities and, in some cases, were trained to take the lead in future wildlife monitoring. Conversely, some northerners visited our universities to exchange knowledge in a way that was beneficial to students and university researchers. For example, a team of experts from Rankin Inlet and Pond Inlet came to Rimouski in 2014 to demonstrate their field skills and to exchange knowledge with university students, as shown in the movie "Northern Wind Southern Ice" (ArctiConnexion 2014).

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CLIMATE ANALYSIS AND SCENARIO DEVELOPMENT FOR THE CANADIAN ARCTIC AND SUBARCTIC

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ABSTRACT

Analyzing climate variability and trends and constructing climate projection scenarios for the Canadian Arctic and Subarctic regions is more challenging than for southern Canadian regions. This is mostly due to the inconsistent and sparse observational datasets, to the complex regional setting and the interlocked physical processes involved in this environment. The main objective of this project is to supply information on observed and projected changes in key climate variables and indicators in support of the ongoing IRIS (IRIS 1-2-3) and AACA* Baffin-Bay-Davis-Strait activities. This requires 1) the acquisition, evaluation and analysis of in situ and reanalysis datasets in the Canadian Arctic; 2) tracking state-of-the-art developments in coupled cryosphere/atmosphere/ocean models and scenario construction methods; and 3) effective communication of scenarios and their uncertainties to users. The purpose of this project is to provide researchers, stakeholders, decision-makers and communities with robust knowledge of current and anticipated climate changes that can be used to support sustainable development in this complex and rapidly changing environment.

*Adaptation Actions for a Changing Arctic (Arctic Council).

KEY MESSAGES

- An evaluation of eight gridded climate and eight reanalysis datasets over the Canadian Arctic (Rapaic et al. 2015) showed that dataset bias and spread exhibited important spatial, seasonal and temporal variability with the largest spread between datasets found over mountain and coastal regions and over the Canadian Arctic Archipelago. Analysis of the temporal consistency of datasets over the 1950-2010 period showed evidence of discontinuities in several datasets as well as a noticeable increase in dataset spread in the period after ~2000. Declining station networks, increased automation, and the inclusion of new satellite data streams in reanalyses are potential contributing factors to this phenomenon. Evaluation of trends over the 1950-2010 period showed a relatively consistent picture of warming and increased precipitation over the Canadian Arctic from all datasets, with the CANGRD dataset giving moistening trends two times larger than the multi-dataset average related to the adjustment of the station precipitation data. The study results indicate that considerable care is needed when using gridded climate datasets in local-regional scale applications in the Canadian Arctic.
- Analysis of Canadian Arctic seasonal temperature trends over 1981-2010 (Figure 1) show a number of regional "hot spots" where fall season warming has exceeded 5.0°C per 30 years e.g. the areas adjacent to Hudson Strait-Foxe Basin, areas around the Beaufort Sea and Amundsen Gulf, and Ellesmere and Baffin Islands. The enhanced warming in these regions is associated with marked declines in sea ice concentration which contributes a positive feedback particularly in the fall period from later ice formation (Parmentier et al. 2013). The Hudson Strait-Foxe Basin region also appears as a "hot spot" in the multi-dataset trend results. Coupled ice-ocean model simulations of the response of the Hudson Bay system to a climate-warming scenario (Joly et al. 2010) showed the ice regime was particularly sensitive to warming due to the heat storage and water circulation characteristics of the Hudson Bay ocean system. The identification of such regions with enhanced climate sensitivity in multiple datasets and climate model simulations can provide important information to local decision makers and for climate monitoring activities.
- The IRIS-2 region has warmed significantly (0.05 confidence level) over the 1950-2013 period in all seasons except spring with mean annual air temperatures (MAAT) increases of 0.27°C per decade over the period. However, most of this warming has occurred since the early-1990s as the 1950-1992 period is characterized by a weak cooling (significant only in spring). The recent period is characterized by strong warming in the fall season (Figure 1) and a later onset to ice cover. 2010 is the warmest year in the IRIS-2 region in the current instrumental climate record; subsequent years have exhibited a relative cooling but this is consistent with the natural variability of the climate in the region which exhibits a strong periodicity around ~4 years.
- The available evidence suggests that the observed warming over the IRIS-2 region has been accompanied by significant increases in total precipitation of ~5% per decade with most of the climate stations in the region showing significant increases in snowfall over the 1950-2013 period. The fraction of total precipitation falling as snow has remained relatively stable around 70% since ~1960.
- Evidence from surface observations and satellite data indicates significant decreases of ~3 weeks in the period with snow on the ground over the IRIS-2 region since 1950 with much of the decrease related to a later start to the snow cover season. The period since ~1980 is characterized by relatively more important shifts to earlier dates of snow disappearance in the spring. Maximum snow depths have decreased over the region by an average of about 20% since 1950.

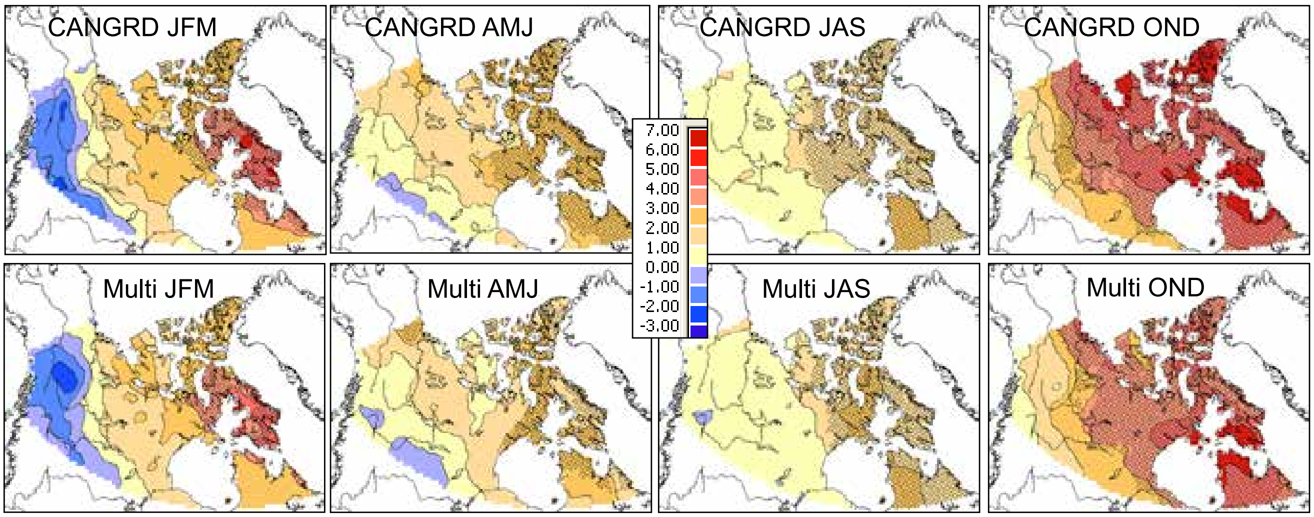

Figure 1. Seasonal patterns of 1981-2010 air temperature trend (°C/30y) in CANGRD (top row) and a 12 dataset average (bottom). Gridpoints with locally significant trends in CANGRD and consensus trends (i.e. > 50% of datasets have locally significant trends of the same sign) in the multi-dataset are indicated with an "x". From Rapaic et al (2015).

- The IRIS-2 region has experienced some of the largest observed decreases in summer sea ice extent in the Canadian Arctic with 20% losses in Baffin Bay over the period from 1979-2008. Most of the change has occurred in the period from 1998 with 2006 having the lowest ice cover in the period with regular satellite observations. Weekly ice thickness measurement made from the late 1950s at communities in the IRIS-2 region show evidence of an abrupt 10% decrease in maximum ice thickness after 1998. Climate models project a continuation of these trends but with a large spread in the magnitude, rate and timing. Recent runs from a high resolution coupled ice-ocean model over the Canadian Arctic Archipelago (CAA) show declining sea ice concentration and thickness but no completely ice-free summers within the CAA before 2100. Multi-year ice has undergone rapid decreases in recent years but is likely to remain a hazard for shipping for the foreseeable future.
- Observations show that most of the land ice in the CAA has lost mass and area over the past century as a result of climate warming, with more intense and sustained melt since 2007. The CAA glaciers are now the single largest land ice contributor to sea-level rise outside Greenland and Antarctica. The indications are that the current observed mass loss trend will likely continue into the future as enhanced meltwater runoff is not sufficiently compensated by increased snowfall. However, it should be stressed that the sign, magnitude and timing of projected changes in snowfall and accumulated snow mass over this region exhibit strong variability between climate models and between emission scenarios.

OBJECTIVES

The main objectives of the project in 2014-15 were:

- To produce climate scenarios for the IRIS-1, -2 and -3 regions [Grenier, Barrette, Brown, Chaumont];
- To contribute knowledge, expertise and scenarios for the Arctic Council AACA (Adaptation Actions for a Changing Arctic) Baffin Bay-Davis Strait regional assessment [Brown, Grenier, Chaumont, Barrette];

- To identify and analyze climate and related data in support of impact and adaptation (I&A) studies and the production of climate scenarios [Grenier, Gennaretti];
- To complete the evaluation of gridded climate data sets of temperature and precipitation over the IRIS regions and submit a journal article for publication [Rapaic, Brown, Markovic, Chaumont];
- To characterize variability and change in the climate and cryosphere of the IRIS regions, and assess the potential of climate models to capture the observed variability and physical processes [Markovic, Grenier, Brown]; and
- To track state-of-the-art developments in climate modelling and scenario development for Arctic climate regions [Grenier, Gennaretti].

INTRODUCTION

This special project is a continuation of the collaboration initiated in 2009 between Ouranos and ArcticNet to develop climate scenarios for the IRIS-4 region (Integrated Regional Impact Study of the Nunavik and Nunatsiavut region). The main objectives of the project range from supplying climate change (CC) information in support of the ongoing IRIS projects (IRIS 1-2-3) to more fundamental research on variability and change in the Canadian Arctic climate. Achieving a thorough knowledge of recent climate trends in the Arctic is challenging considering the sparse distribution of climate stations and the lack of consistency between available data sets. In this context, it is crucial to characterize the uncertainties in the observations. Climate change scenario construction in the Canadian Arctic and Subarctic regions also requires special attention due to the complex regional settings, the strong influence of sea ice on coastal climate, and important physical processes such as blowing snow transport and sublimation that may not be adequately included in climate models.

ACTIVITIES

1. Evaluation of gridded climate datasets and estimation of climate trends

The spatial and temporal consistency of seasonal air temperature and precipitation in eight widely-used gridded observation-based climate datasets (CANGRD, CRUTS3.1, CRUTEM4, GISTEMP, GPCC, GPCP, HadCRUT3, UDEL) and eight reanalyses (20CR, CFSR, ERA40, ERA-interim, JRA25, MERRA, NARR, NCEP2) was evaluated over the Canadian Arctic for the 1950-2010 period. This study was initiated in response to findings of marked differences between datasets over northern regions of Canada even though they share common sources of information. The results are highlighted in the key messages above and in the results section below. The study has been accepted for publication in Atmosphere-Ocean (Rapaic et al. 2015).

2. Climate change scenario development

F. Gennaretti, L. Sangelantoni and P. Grenier carried out an evaluation at Canadian Arctic coastal locations of methods for downscaling temperature and precipitation from climate models that preserve the interdependence of the two variables. Failure to take account of this interdependence can result in unrealistic temperature-precipitation joint behaviour and thus, for example, unrealistic characterisation of extreme events. A two-dimensional statistical adjustment and downscaling method was proposed and tested with results reported below.

3. Contribution to IRIS-1 and IRIS-2 Climate Chapters

R. Brown and C. Barrette provided updates and revisions to the IRIS- 1 Climate Chapter being led by D. Barber and L. Candlish. C. Barrette and R. Brown are coordinating the writing of the climate section for the IRIS-2 report which includes an analysis of climate and cryospheric observations and climate model output, review of literature, and presentation of climate scenarios. Key findings from this work are included in the key messages/results section of this report. R. Brown also provided an overview presentation of observed and projected climate change over the Eeyou Marine Region (James Bay and eastern Hudson Bay) based on climate analysis and simulations carried out at Ouranos.

4. Contribution to ACAA Baffin Bay-Davis Strait Assessment

D. Chaumont, R. Brown and P. Grenier are collaborating with Dr. Peter Lang Langen of the Danish Climate Centre in the coordination and preparation of the climate drivers section of the Adaptation Action for a Changing Arctic report for the Baffin Bay-Davis Strait region. This includes a synthesis of regional climate drivers, a summary of observed changes, as well as climate change projections for key climate variables.

5. Evaluation of CMIP5 climate model simulations

An initial evaluation was carried out by M. Markovic of the ability of the recent suite of CMIP5 climate model simulations at representing the seasonal cycle in key climate variables over northern Canada. Unfortunately M. Markovic left Ouranos for a position at Environment Canada in April 2014 before the results of this work were written-up and submitted for publication. Preliminary results are included in an Ouranos progress report (Markovic et al. 2014) and are summarized in the results section.

RESULTS

1. Evaluation of gridded climate datasets and estimation of climate trends

The spatial and temporal consistency of seasonal air temperature and precipitation in eight widely-used gridded observation-based climate datasets (CANGRD, CRUTS3.1, CRUTEM4, GISTEMP, GPCC, GPCP, HadCRUT3, UDEL) and eight reanalyses (20CR, CFSR, ERA40, ERA-interim, JRA25, MERRA, NARR, NCEP2) was evaluated over the Canadian Arctic for the 1950-2010 period (Rapaic et al. 2015). The evaluation used the CANGRD dataset as a reference which is based on homogenized temperature and adjusted precipitation from climate stations (Vincent et al. 2012, Mekis and Vincent 2011). Dataset agreement and bias were observed to exhibit important spatial, seasonal and temporal variability over the Canadian Arctic with the largest spread between datasets over mountain and coastal regions and over the Canadian Arctic Archipelago. Reanalysis datasets were typically warmer and wetter than surface observation based datasets with CFSR and 20CR exhibiting biases in total annual precipitation on the order of 300 mm. Warm bias in 20CR exceeded 12°C in winter over the western Arctic. Analysis of the temporal consistency of datasets over the 1950-2010 period showed evidence of anomalous values in several datasets as well as a noticeable increase in dataset spread in the period after ~2000.

Evaluation of trends over the 1950-2010 showed a relatively consistent picture of warming and increased precipitation over the Canadian Arctic from all datasets, with CANGRD giving moistening trends two times larger than the multi-dataset average related to the adjustment of the station precipitation data. The more recent 1981-2010 period was characterized by stronger warming over the eastern Arctic in the October-December period, with warming at a number of regional "hot spots" exceeding 5°C/30 y (Figure 1).

2. Climate change scenario development

Current and future climate change is and will be especially pronounced in the Arctic regions and, in order to improve impact studies, we need to produce more realistic climate scenarios, especially for the coastal zones where most of the northern residents live. One important aspect of local climates, in the Arctic as well as elsewhere, is the interdependence between temperature and precipitation. This interdependence is often complex and can be described in part by simple correlations and more completely by bivariate probability distributions. However, up to now, few studies have investigated whether climate models are able to realistically reproduce this climatic characteristic and how to develop climate scenarios in which the temperature-precipitation interdependence is well reproduced. Failure to take account of this interdependence can result in unrealistic temperature-precipitation joint behaviour and thus, for example, unrealistic characterisation of extreme events.

To assess this issue for the Canadian Arctic, Fabio Gennaretti (Ouranos) and colleagues Lorenzo Sangelantoni (Università Politecnica delle Marche, Ancona, Italy) and Patrick Grenier (Ouranos) carried out a study of the temperature-precipitation interdependence in observations and model outputs at Canadian Arctic coastal sites. A two-dimensional (2D) statistical adjustment and downscaling method was proposed (following and improving on Piani and Haerter 2012) and tested to improve the local climate scenarios based on climate model outputs. The NRCan gridded interpolated Canadian database of daily temperature and precipitation for 1950-2010 was used as the benchmark to assess the interdependence realism in an ensemble of model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5). The analysis included an investigation of how model temperature-precipitation dependence structures at study sites are modified by commonly used one-dimensional (1D) post-processing methods compared to the proposed 2D post-processing technique that preserves the observed temperature-precipitation correlation structure. The following preliminary conclusions were obtained from the analysis carried out to date:

- The higher a site's latitude, the greater the probability that the distributions of the raw modeled data (either temperature or precipitation) diverge from the observed ones and the more likely it is that the temperature-precipitation interdependence in the models becomes unrealistic.
- The 2D method gives comparable results to the 1D method (Figure 2).
- The 2D statistical adjustment outperforms raw and 1D corrected simulation data in the reproduction of the observed temperature-precipitation interdependence.
- Where the temperature-precipitation interdependence is important (e.g. for characterization of extreme events and of sea ice volume variability), 2D statistical adjustments should be used for the production of local climate scenarios in the Arctic.
- Future work will involve testing the proposed 2D method with other climatic variables (e.g. radiation, wind and humidity), and the development of better ways to characterize the uncertainties in simulated and observed data. This is especially important in the Arctic where the network of weather stations is sparse and trace events (<0.3 mm per day) are frequent (>100 days per year) and can account for more than 10% of total precipitation. It is also planned to

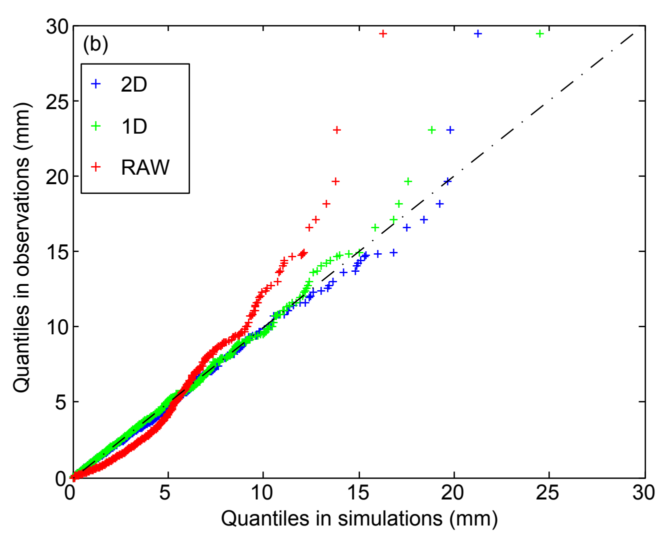

Figure 2. Quantile-Quantile plot of observed and downscaled precipitation (1D and 2D methods) from MIROC-ESM for Resolute.

compare the performance of the proposed 2D statistical adjustment with that of other post-processing methods used to handle inter-variable dependence (e.g. Hoffmann and Rath 2012, Ben Alaya et al. 2014). A paper describing this work is being developed for submission to JGR. The higher a site's latitude, the greater the probability that the distributions of the raw modeled data (either temperature or precipitation) diverge from the observed ones and the more likely it is that the temperature-precipitation interdependence in the models becomes unrealistic.

- The 2D method gives comparable results to the 1D method (Figure 2).
- The 2D statistical adjustment outperforms raw and 1D corrected simulation data in the reproduction of the observed temperature-precipitation interdependence.
- Where the temperature-precipitation interdependence is important (e.g. for characterization of extreme events and of sea ice volume variability), 2D statistical adjustments should be used for the production of local climate scenarios in the Arctic.

Future work will involve testing the proposed 2D method with other climatic variables (e.g. radiation, wind and humidity), and the development of better ways to characterize the uncertainties in simulated and observed data. This is especially important in the Arctic where the network of weather stations is sparse and trace events (<0.3 mm per day) are frequent (>100 days per year) and can account for more than 10% of total precipitation. It is also planned to compare the performance of the proposed 2D statistical adjustment with that of other post-processing methods used to handle inter-variable dependence (e.g. Hoffmann and Rath 2012, Ben Alaya et al. 2014). A paper describing this work is being developed for submission to JGR.

3. Contribution to IRIS-1 and IRIS-2 Climate Chapters

The IRIS-1 report was approaching final copy-edit at the time of writing and R. Brown and C. Barrette provided extensive comments and revisions (Feb. 12, 2015). Analysis of observed change in climate over the IRIS-2 region has made extensive use of the Environment Canada homogenized temperature and adjusted precipitation datasets of Vincent et al. (2012) and Mekis and Vincent (2011). This has been supplemented with data from a number of other sources such as reanalyses, satellite data as well as reviews of the published scientific literature. The climate change projections developed for the IRIS-2 region follow the same methodology used in IRIS-4 and IRIS-1 (i.e. dynamically downscaled CMIP3 SRES A2 scenario output for 2050 from eight CRCM4 runs) and were published in July 2013 as an internal ArcticNet document (Barrette 2013) for consultation by the various authors contributing to the IRIS-2 report. This information is supplemented with analysis from CMIP5 output for certain variables such as sea ice and snow cover. An external review of the IRIS-2 draft climate chapter is planned for March 2015 with subject matter experts. A summary of some of the key/interesting findings is included below. Note that variability and change in the ground thermal regime is treated in another chapter of the IRIS-2 report.

The number of climate stations in the IRIS-2 region varies markedly over time (Figure 3) which limits the period for climate analysis from ~1950. The station density reached a peak in the 1960s and remained relatively stable until a rapid decline in the 1990s. This decline is more marked for precipitation and the period since 2009 has fewer than 5 stations in the region with monthly precipitation data in the Vincent et al. (2012) dataset.

Surface air temperature

Analysis of the regionally-averaged climate station data indicate the IRIS-2 region has warmed significantly (0.05 confidence level) over the 1950-2013 period in all seasons

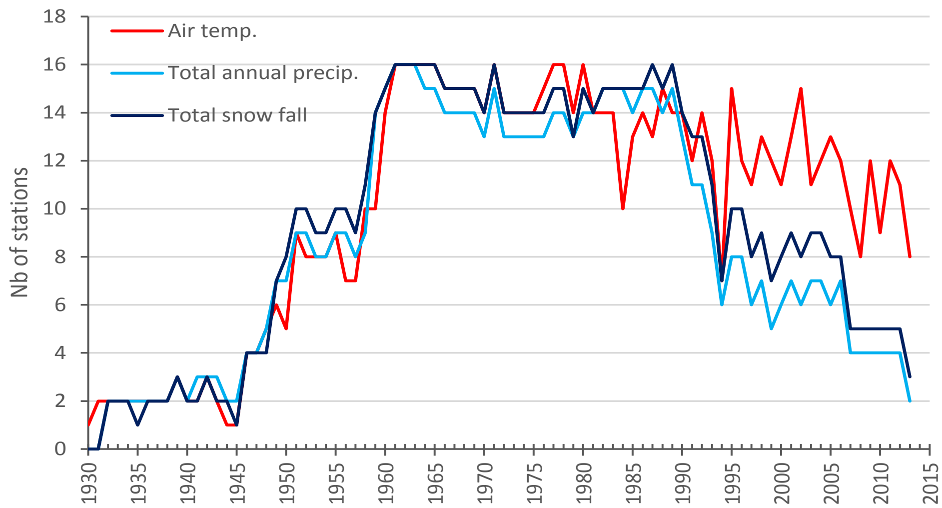

Figure 3. Number of stations in the IRIS-2 region with non-missing annual temperature and total precipitation values in the homogenized temperature and adjusted precipitation datasets of Vincent et al (2012) and Mekis and Vincent (2011). In any single month there may be more stations than shown as a valid annual value requires having complete data in that year.

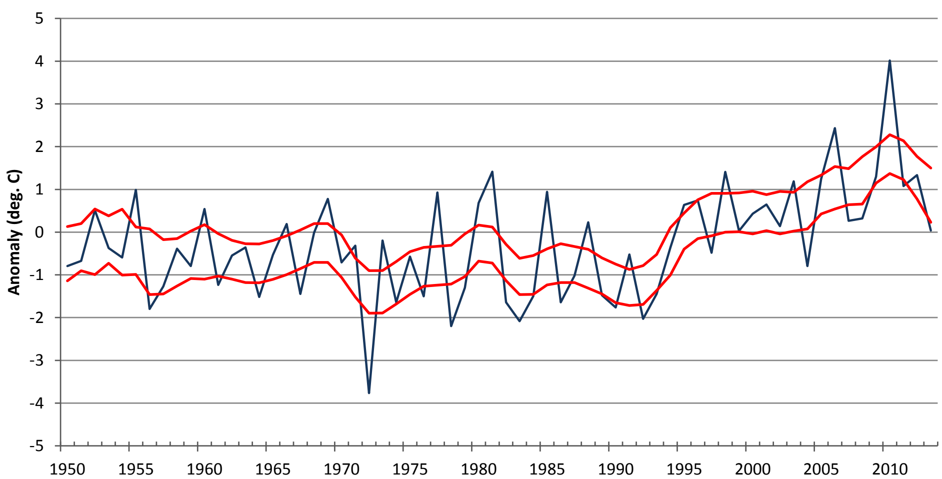

Figure 4. Regionally-averaged mean annual temperature anomaly (blue curve) for IRIS-2 region from 17 climate stations with binomially filtered 95% confidence interval (red curves) estimated from the average correlation between-stations following Wigley et al. (1984). Data are computed from the homogenized monthly air temperature dataset of Vincent et al. (2012).

except spring with mean annual air temperatures (MAAT) increases of 0.27°C per decade over the period. However, most of this warming has occurred since the early-1990s as the 1950-1992 period is characterized by a weak cooling (significant only in spring) (Figure 4). The period from 1993 is characterized by strong significant warming in MAAT of 0.90°C per decade (0.05 confidence level) that is mainly driven by warming in the fall and winter. 2010 is the warmest year in the 1950-2013 period and subsequent years have exhibited a relative cooling consistent with the natural variability of the climate in the region which exhibits a strong periodicity around ~4 years. Climate change projections for 2050 (with regard to 1971-2000 period) suggests relatively low warming ~2-3°C over most of the region from April to September (Figure 5) with more pronounced warming ~5°C in fall (OND) and winter (JFM).

Precipitation

The available evidence suggests that the observed warming over the IRIS-2 region has been accompanied by significant increases in total precipitation of ~5% per decade (Figure 6) with most of climate stations in the region showing significant increases in snowfall over the 1950-2013 period. One contributing factor in these snowfall increases is the relatively unchanged duration of the period with below-freezing temperatures (freeze-onset date minus thaw-onset date) since 1950. The fraction of total precipitation falling as snow has also remained relatively stable around 70% since ~1960. It should be noted that the precipitation increase over the 1950-2013 period shown in Figure 6 is strongly influenced by what may be anomalously low precipitation values in the 1950s and the large positive anomaly in 2013. The 1950s period is characterized by solid precipitation fractions that are markedly lower than the rest of the data record suggesting that snowfall was underestimated. Precipitation is projected to increase over most of the IRIS-2 region by 10-30% with the largest relative increases in the winter and fall (Figure 5) and over northern parts of the region.

Snow Cover

Evidence from surface observations and satellite data indicates significant decreases of ~3 weeks in the period with snow on the ground over the IRIS-2 region since 1950 (Figure 7) with much of the decrease related to a later start to the snow cover season. The period since ~1980 is characterized by relatively more important shift to earlier dates of snow disappearance in the spring. Maximum snow depths have decreased over the region by an average of about 20% since 1950 however this may not reflect accumulation trends over vegetated areas as snow depth observations are made at climate stations in open terrain that may not be representative of snow conditions in the prevailing land cover. For example, observations of snow depth made at climate stations will not reflect the impact of the increasing shrub expansion over tundra that has

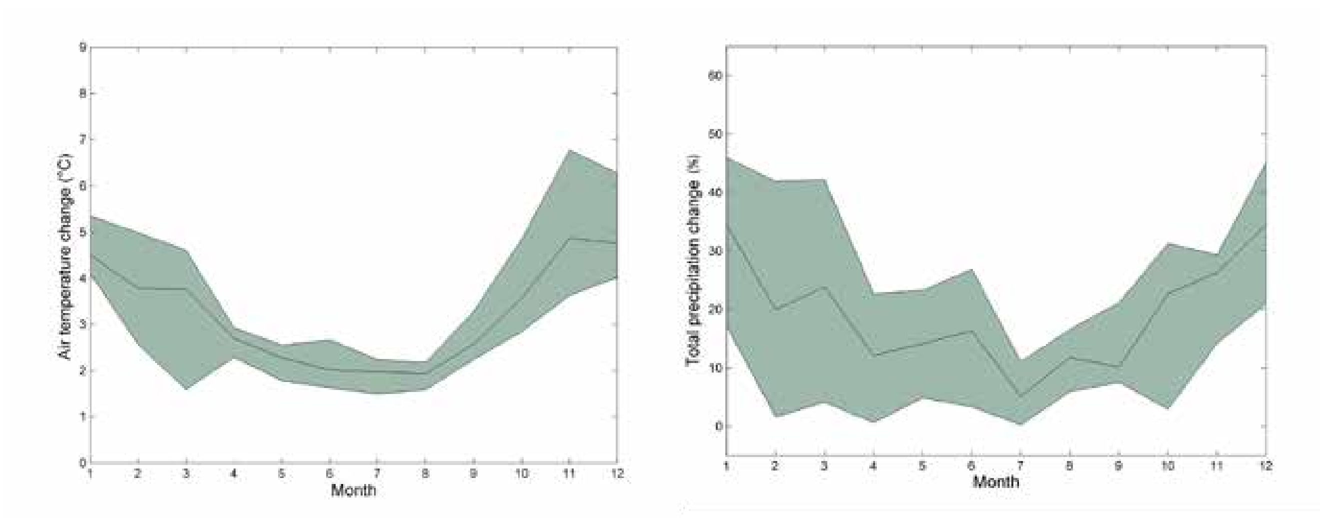

Figure 5. Seasonal median and range of projected changes in monthly mean air temperature (left panel) and total seasonal precipitation (right panel) from eight CRCM runs for 2050 (with regard to 1971-2000 reference period) averaged over all the grid cells of the IRIS-2 region. The outer lines represent the range of the eight simulations.

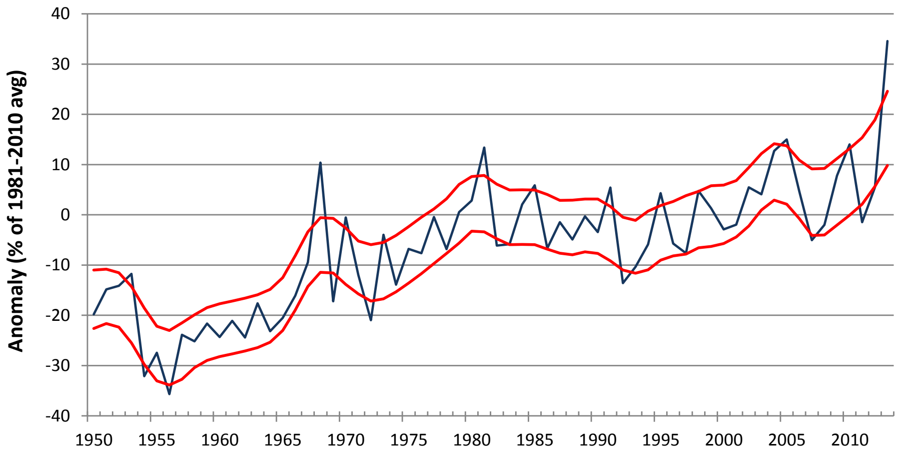

Figure 6. Regionally averaged total annual precipitation anomalies (% of 1981-2010 mean annual precipitation) for 10 stations in the IRIS-2 region. Data is from the 2013 update of the Environment Canada adjusted precipitation dataset (Mekis and Vincent 2011). The 9-term binomially filtered 95% confidence intervals (red curves) are estimated from the average correlation between-stations following Wigley et al. (1984).

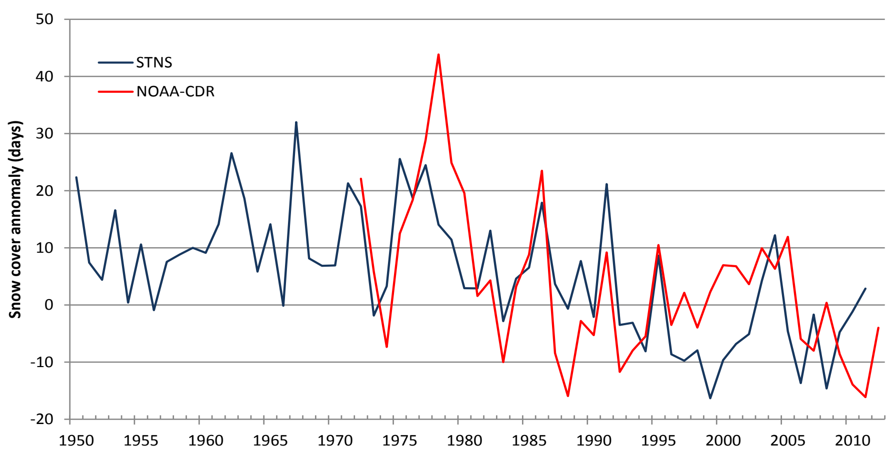

Figure 7. Regionally-averaged anomalies (days) in annual snow cover duration from surface stations (STNS) and the NOAA-CDR satellite dataset (Robinson et al. 2012) over the IRIS-2 region. Anomalies are computed with respect to a 1981-2010 reference period.

important impacts on snow accumulation, snowpack physical properties, energy exchanges and climate feedbacks (Marsh et al. 2010, Loranty and Goetz 2012). Estimates of trends in maximum annual snow water equivalent (SWEmax) over Arctic land areas from satellite data (e.g. GlobSnow, Takala et al. 2011) and reanalysis-driven reconstructions (e.g. Liston and Hiemstra 2011) show trends of opposite sign over the IRIS-2 region. Climate change projections for the region also show a range in SWEmax response to warming from +10 to -10% for 2050 compared to 1971-2000 period (Figure 8) with the 16-global model average close to zero. Dynamically downscaled climate model output from the Canadian Regional Climate Model, CRCM4 (Barrette 2013) indicate increases in annual maximum accumulation over southern Baffin

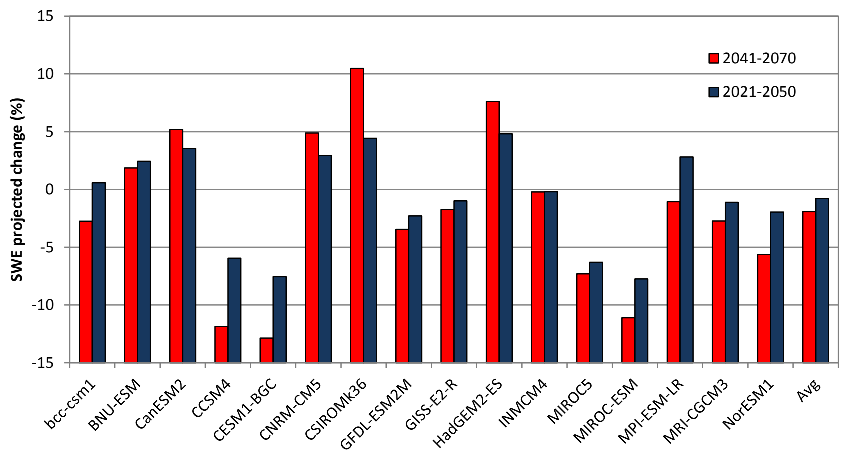

Figure 8. Projected change (% with respect to 1976-2005 mean) in regionally-averaged maximum annual monthly SWE over land areas in the Baffin Bay-Davis Strait region (60-95N, 45-95W) for 2030 and 2050 from 16 CMIP5 models run with the RCP8.5 emission scenario.

Island with slight decreases in other areas. This pattern resembles the 1979-2009 trends in the Liston and Hiemstra (2011) reconstruction (not shown).

Sea Ice

The IRIS-2 region has experienced some of the largest observed decreases in summer sea ice extent in the Canadian Arctic with 20% losses in July-November sea ice extent over the period from 1981-2014 (Figure 9). Most of the change has occurred in the period from 1998 with 2006 having the lowest ice cover in the period with regular satellite observations. The observed declines in sea ice over the region are part of a pan-Arctic and pan-cryospheric response to warming (Derksen et al. 2012) that is underestimated in current climate models (Stroeve et al. 2012). Analysis of trends in ice concentration from passive microwave satellite data (Figure 10) show that the ice concentration has been decreasing in nearly all months in the IRIS-2 region. Within the IRIS-2 region Baffin Bay, Hudson Strait and Davis Strait have experienced some of the largest decreases in summer total and multi-year sea ice area in the Canadian Arctic (Howell et al. 2009, Tivy et al. 2011). These ice changes are reacting to (and providing positive feedbacks to) increasing air and sea-surface temperatures, and changes in atmospheric circulation (Overland et al. 2012, Sharp et al. 2014; Petrie et al. 2015) that are driving the rapid rates of climate change observed over the region in the past decade. Climate models project a continuation of these trends but with a large spread in rate and timing of sea ice changes (Collins et al. 2013, Semenov et al. 2015). Wang and Overland (2012) determined a model consensus for nearly ice-free Arctic summers by the 2030s using a sub-set of models that best represented the observed sea ice regime and historical trends. However, most of these models do not resolve the CAA and the ice dynamics of the region that involves the import of multi-year ice (MYI) from the Arctic Ocean (Howell et al. 2008, 2009, 2013). Sea ice change scenarios for the Canadian Arctic with a high resolution coupled ice-ocean model (Hu and Myers 2014) do not show completely ice-free summers in the CAA before 2100 in agreement with Sou and Flato (2009). The future response of MYI depends on factors in addition to temperature (Derksen et al. 2012) and is likely to remain a hazard for shipping for the foreseeable future. Additional simulations from high resolution coupled ice-ocean models driven with a range of climate model

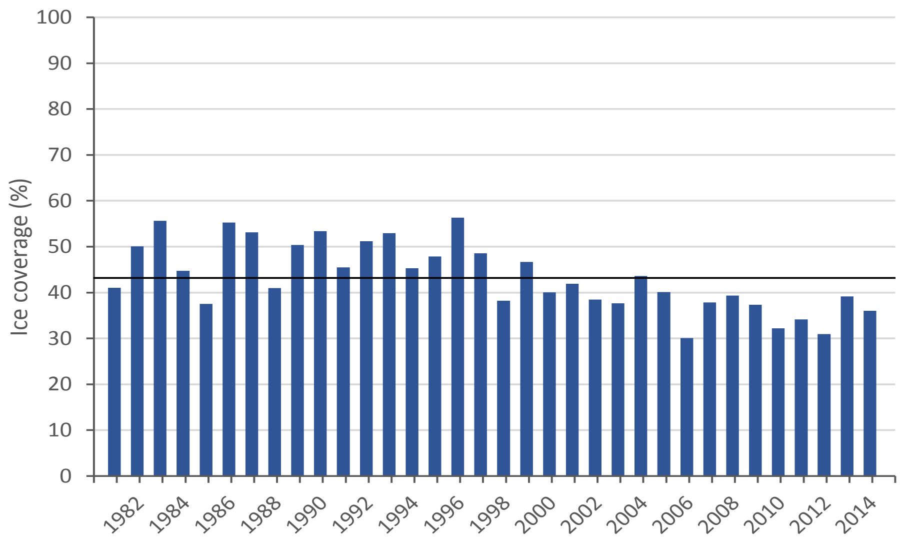

Figure 9. July-November sea ice cover (%) over the Eastern Canadian Arctic zone as defined by the Canadian Ice Service for the period 1981-2014. The black line is the median ice extent from 1981-2010. Source: Canadian Ice Service (http://ice-glaces.ec.gc.ca/App/WsvPrdCanQry.cfm?CanID=11090&Lang=eng).

output are needed to reach robust conclusions about the projected rates of change in IRIS-2 sea ice cover.

Trends in landfast ice are highly relevant to local communities as the coastal ice corridor has significant social, cultural, and economic importance. Analysis of U.S. National Ice Center weekly sea ice charts from 1976 to 2007 by Yu et al. (2014) show that landfast ice extent around the Arctic Basin was relatively extensive from the early to mid-1980s but has since declined in many coastal regions of the Arctic, particularly after the early 1990s. Analysis of Canadian landfast ice conditions with Canadian Ice Service (CIS) digital charts from 1983 to 2009 by Galley et al. (2012) showed significant decreases in landfast ice cover duration over the CAA from later ice onset and/or earlier breakup. The study identified a number of Arctic communities where the landfast ice regime had undergone particularly large changes (Tuktoyaktuk, Kugluktuk, Cambridge Bay, Gjoa Haven, Arctic Bay, and Pond Inlet). Landfast sea-ice duration in the interior of the Northwest Passage was not observed to have undergone any statistically significant change over the period analyzed. Analysis of weekly ice thickness data from six coastal communities in the IRIS-2 region with long-term weekly ice thickness measurements from the late-1950s show maximum ice thicknesses experiencing a step decrease of ~20 cm after 2000 which represents about a 10% reduction in maximum thickness (Figure 11). The regionally-averaged date of annual maximum ice thickness (not shown) advanced by ~3 weeks over the same period in response to earlier melt.

Glaciers and Ice Caps

The Canadian Arctic contains the largest area of land ice (~150,000 km^2) on Earth outside the ice sheets of Greenland and Antarctica and recent estimates of mass loss makes the Canadian Arctic Archipelago the single largest land ice contributor to sea-level rise outside Greenland and Antarctica (Gardner et al. 2011, Sharp et al. 2011, Gardner et al. 2013, Sharp et al. 2014). Observations show that most of the land ice in the CAA has lost mass and area over the past century as a result of climate warming, with more intense and sustained melt since 2007 in response to a trend to more frequent summer anticyclonic circulation over the region that is only weakly replicated by

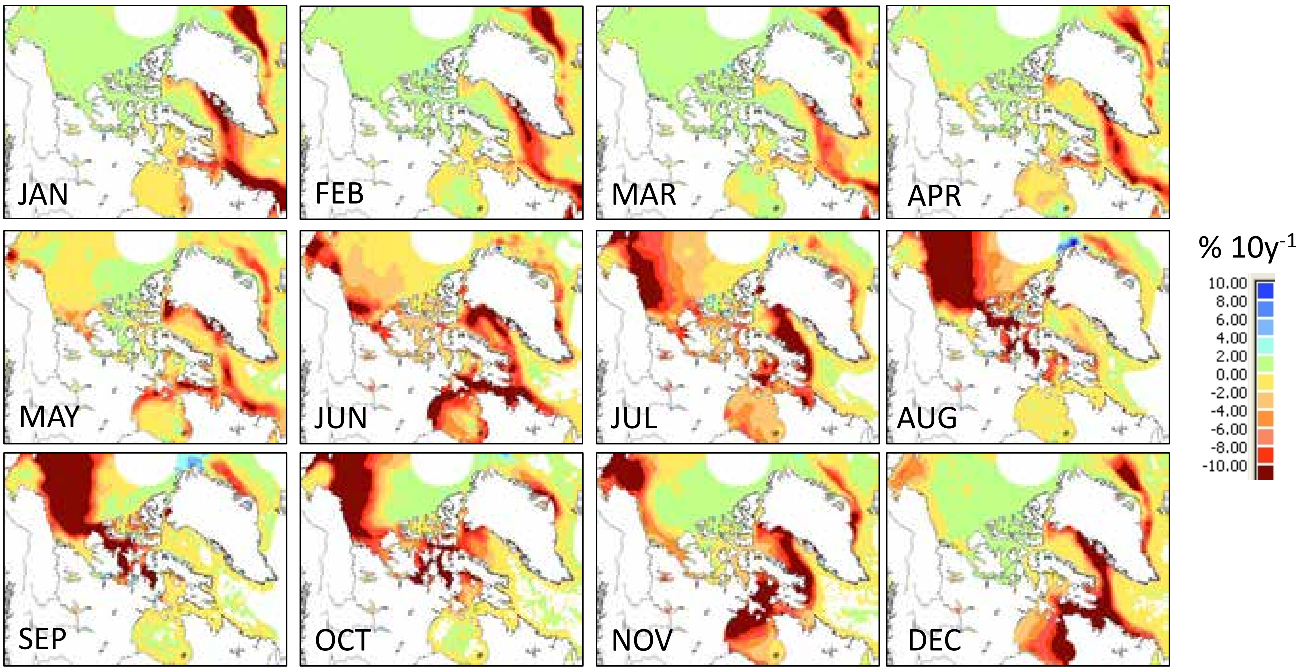

Figure 10. 1979-2012 trend (% per decade) in monthly average ice concentration (%) over the Canadian Arctic and adjacent waters based on the passive microwave satellite dataset of Cavalieri et al. (1996, updated to 2012).

CMIP5 climate models (Overland et al. 2012, Petrie et al. 2015). This finding is consistent with other studies showing climate models systematically underestimating the observed cryospheric response to warming over the Arctic (e.g. Stroeve et al. 2012, Derksen and Brown 2012). Floating ice shelves in northern Ellesmere Island have also been strongly affected by this recent warming with some fjords in the region now ice free for the first time in over 3000 years (Sharp et al. 2014, White et al. 2014).

The observed glacier mass losses are dominated by melt/runoff with calving playing a varying role (Williamson et al. 2008, Van Wychen et al. 2014). The indications are that the current observed mass loss trend will likely continue into the future as enhanced meltwater runoff is not sufficiently compensated by increased snowfall (Lenaerts et al. 2014). However, it should be stressed that there is considerable model variability in the sign, magnitude and timing of projected changes in snowfall and accumulated snow mass over this region, and most climate models do not represent local moisture sources such as the North Open Water polynya that is an important contributor to the mass balance of the Manson and Prince of Wales Ice Caps (Boon et al. 2011).

4. Contribution to ACAA Baffin Bay-Davis Strait Assessment

This work is ongoing and there are few significant results to present at this time. Figure 8 is an example of the snow cover change scenarios being developed for the assessment which shows a range in the magnitude and sign of projected changes in seasonal snow mass over the region with climate model. Preliminary temperature (tmax, tmin), precipitation and wind speed scenarios were developed from the CMIP5 ensemble and supplied to the ACAA BBDS project for input to a regional scenario framework model for assessing cumulative effects of climate and socio-economic change.

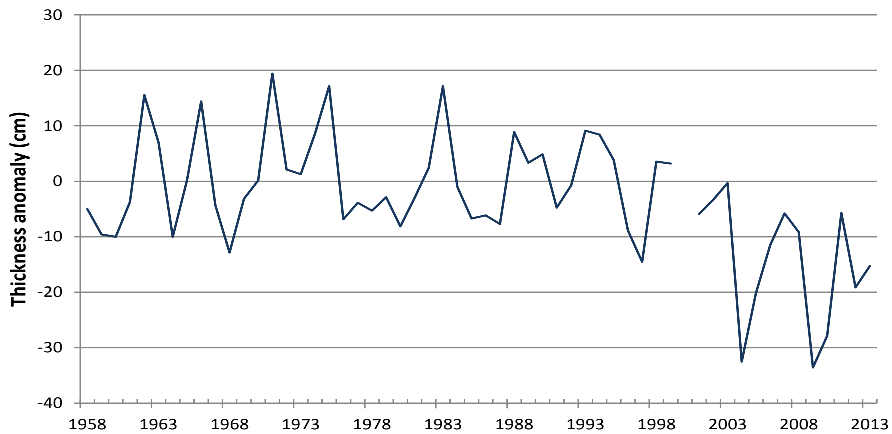

Figure 11. Regionally-averaged annual maximum ice thickness anomalies (with respect to the 1959-1987 average) from six stations in the IRIS-2 region. Ice thickness data were obtained from the Canadian Ice Service.

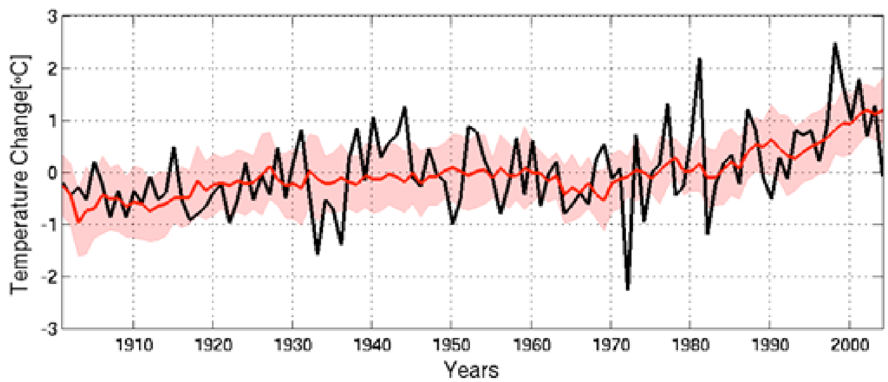

Figure 12. Comparison of observed Canadian Arctic-averaged (57-90°N, 215-306°E) mean annual air temperatures from CRU (black) with the CMIP5 multi-model mean (red) over 1900-2005. The model spread (± one standard deviation) is shown in pink.

5. Evaluation of CMIP5 climate model simulations

An initial evaluation of the recent suite of CMIP5 climate model simulations over northern Canada showed that the multi-model ensemble performed well at capturing the long-term variability in air temperatures including the period of rapid warming that started after ~1980 (Figure 12). An assessment of the ability of the models at representing key components of the current Canadian Arctic climate was carried out following the variability index approach of Reichler and Kim (2006) which provides a measure of how well a model replicates the observed mean climate and interannual variability. The components selected for evaluation were annual and seasonally-averaged values of air temperature, precipitation, sea level pressure and solar radiation. This process identified a number of models that did not perform as well (e.g. FIO-ESM, the MIROC suite of models, CMCC-CMS and GFDL). Removing these models from the ensemble reduced the model spread in precipitation, sea level pressure and solar radiation but had little impact on air temperature. The representation of the seasonal cycle was found to be the most important metric to evaluate as this influences interannual variability and climate change response (Hall and Qu 2006). In general all the CMIP5 models provided good representation of the seasonal cycles for air temperature, precipitation, sea ice and snow water equivalent (SWE). The exceptions were FIO-ESM for the seasonal precipitation cycle, and CSIRO-Mk3-6-0 and INMCM4 for SWE.

DISCUSSION

The Canadian Eastern Arctic is currently experiencing the most rapid warming of anywhere in Canada in the autumn and early winter period. According to the climate station air temperature record, this rapid warming has only really kicked-in since the early 1990s and is linked to both natural and anthropogenic factors with several anomalously warm years being primarily linked to anomalies in the Arctic Oscillation and North Atlantic sea surface temperatures (Way and Viau, 2014). This underscores the need to understand how and to what extent these major modes of natural variability may change in the future given their important role in climate extremes in this region.

Cryospheric indicators of change over the region such as snow and ice cover and glacier mass balance show evidence of longer-term decreases as these respond to a range of forcing mechanisms and time scales that are not necessarily reflected in air temperature series from coastal stations. Understanding how all the pieces of the climate puzzle fit together is a challenge especially when we find evidence that the consistency between climate and reanalysis datasets has decreased markedly over northern Canada over the last decade. Evaluating climate models in this environment is a challenge when the differences between observational datasets can be as large as or larger than the differences between climate models. Another concern is a growing body of evidence that climate models are likely underestimating the response of the Arctic cryosphere to warming. One approach to this problem is selecting subsets of climate models that best represent the observed seasonal cycles and historical trends of key variables following Way and Overland (2012). However, this involves a trade-off in the diversity of models included in a scenario.

ArcticNet funded work in 2015-2018 will be addressing a number of these challenges through the development of improved methods for climate scenarios in the Canadian Arctic i.e. the consideration of observational uncertainty in scenarios, and the role of inter-variable dependences on extremes in temperature and precipitation. The scenario construction methods will also be tested in specific applications (e.g. modelling ice and wave conditions in the coastal zone around communities) that provide community-level information for adapting to a changing climate.

CONCLUSION

The work carried out in this project in 2014-15 has highlighted the rapid rate of warming and reductions in snow and ice cover experienced over the eastern Canadian Arctic over a relatively short period of time. This echoes the findings of Derksen et al. (2012) that the pace of change over the Canadian Arctic has increased in recent years. The trend analysis of Rapaic et al. (2015) showed that the recent warming is concentrated over the eastern Canadian Arctic with a number of “hot spots” with faster rates of warming linked to the regional sea ice regime. Recent studies have demonstrated an important positive feedback of declining sea ice extent over the Canadian eastern Arctic involving the development of positive anticyclonic anomalies in the summer atmospheric circulation that promotes enhanced melt. This feedback mechanism is only weakly captured in climate models and is additional evidence that current climate models are likely underestimating the climate and cryosphere response of the eastern Arctic to global warming. Future work will focus on the issue of how best to downscale climate model information in the Arctic for local applications, the impact of increasing greenhouse effect on extremes in temperature and precipitation, and evaluation of higher resolution (~25 km) RCM runs from the Arctic CORDEX experiment.

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POPULATION DYNAMICS OF MIGRATORY CARIBOU IN NUNAVIK/NUNATSIAVUT

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ABSTRACT

Migratory caribou are central to the economy and traditional life of northern peoples. They are also economically important for a major outfitting industry, much of it involving Aboriginals. Scientific and Aboriginal Traditional Knowledge, however, indicate that populations of migratory caribou undergo drastic changes over several decades. Caribou herds are declining almost everywhere in Canada, and the factors responsible for those declines are still poorly known. Caribou also face the impact of expanding resource-extraction industries, and threats to their habitat will continue to increase with the development of the North, and from climate change. Through the cooperation of government agencies, Aboriginal groups and industry partners we are combining existing long-term data, population genetics studies, monitoring caribou and their predators with satellite collars, satellite-derived information on plant productivity and small-scale climate and browsing manipulations to establish how climate and population density affect the food resources of caribou, their habitat use, choice of calving site, body growth and condition, recruitment, predation and age-specific survival. These are the most important factors currently thought to affect caribou abundance and distribution in the Arctic. We are also addressing the effects of industrial activities on caribou ecology and quantifying the impact of caribou on vegetation in key seasonal ranges. In addition to identifying the factors responsible for changes in population size and distribution, our work will provide managers and Aboriginal Peoples with new tools to monitor the demography of caribou and therefore improve their conservation in the face of climate change.

KEY MESSAGES

- Caribou calves were 8% heavier at birth and 20% heavier at weaning in a herd at low population size (i.e. Rivière-George herd) compared to one at high population size (i.e. Rivière-aux-Feuilles herd). These results suggest that the impact of population size may differ depending on season, because of different energetic demands faced by mothers and offspring.
- Adult female mass and hind foot length in spring predict pregnancy rates in caribou.
- We developed a life history model that can be used to estimate population sizes between aerial censuses. Our results allowed us to precise the 2001 population census for the Rivière-aux-Feuilles herd, with an estimate of 630 000.
- We found that the probability of survival of caribou with heavy radio-collars (1.6 kg) was significantly smaller than those with light collars (0.5 kg).
- We found significant negative impacts of climatic conditions on the survival of caribou only for the declining population of Rivière-George, and those impacts were greater for yearlings than for adults.
- Despite a recent re-definition and expansion, our work revealed that legally designated Wildlife Habitats in Québec on average protected less than 20% of the Rivière-George and Rivière-aux-Feuilles calving grounds. Clearly, protection of calving grounds must consider the dynamic use of space by adult females.
- The fall migration patterns of migratory caribou in Northern Quebec and Labrador had tended to stabilise in recent years. Changes in the spring and fall migratory routes occurred simultaneously with changes in the use of winter ranges. In both seasons, snow conditions seem to be the key factor driving changes in migratory behavior.
- The effect of the demography of both herds on fall migration patterns of the Rivière-aux-Feuilles herd seem to reflect a competition for the southern winter range between herds but also between individuals from the Rivière-aux-Feuilles herd. Indeed, the presence of the Rivière-George herd at high population size appeared to constrain the Rivière-aux-Feuilles herd to the northern winter range.
- Differences in departure and arrival dates between the two herds are likely related to differences in the length of their migrations, caribou from the Rivière-aux-Feuilles herd migrating over a distance twice as long as those of the Rivière-George herd.
- Resource availability on winter and summer ranges influenced the departure dates of caribou for the spring and fall migrations.
- We found evidence that green forage abundance on the calving grounds of migratory caribou is negatively correlated with calving period foraging and trampling pressure.
- Our results supported by both microsatellites and mtDNA divided populations of Rangifer into two geographically structured lineages, one originating from and confined to North-Eastern America, the other originating from Euro-Beringia but also currently distributed in Western North America.
- Forecasting the range of the species in 2080, we predict a strong modification of the distribution of caribou. Under the severe climatic warming scenario considered, our model predicts the distribution of caribou to become even more restricted to high latitudes than today, with possible extinctions in the most southern regions.
- We developed a framework for delineating Conservation Units for caribou that is an effective tool to disentangle units based on genetic and ecological criteria.
- We demonstrated the influence of temporal variation in individual habitat use for inferring the influence of landscape features on gene flow.

- We found discrepancies between genetic and ecotype designation, suggesting convergence of morphological, life-history and behavioral traits across the species distribution range.
- Our results provide strong evidence that both geographic distance and environment contributed to the evolution of spatial genetic divergence in the landscape adaptive radiation of caribou.
- Caribou from the Rivière-aux-Feuilles and Rivière-George herds harbored higher *Besnoitia tarandi* burden compared to the other herds sampled in North America.
- Our results on abundance and diversity of parasite fauna in 12 caribou herds suggest that for most parasites, their distribution is relatively uniform among all herds and that there is no significant difference in terms of prevalence and intensity between sexes, seasons, and herd size, but that adults show a higher prevalence than calves for some parasites.
- Our broad survey of caribou health across 12 caribou herds showed that giant liver flukes (*Fascioloides magna*) were present only in the two Québec herds, with Rivière-George herd having a higher prevalence than the Rivière-aux-Feuilles herd. The prevalence of giant liver flukes was also higher during the population size peak and afterwards than at other times, suggesting the importance of population size in the transmission of these parasites.
- Our results highlight that the potential for compensatory growth in dwarf birch is surpassed under heavy browsing pressure independently of the fertilisation regime. In the context of the worldwide decline in caribou herds, the reduction in browsing pressure could act synergistically with global climate change to promote the current shrub expansion reported in subarctic regions.
- Our study confirms the strong top-down effect of herbivory in interactions with edaphic and climatic factors on caribou forage.
- Ours results strongly suggest that birch growth is co-limited by nitrogen and phosporous availability across its range.
- Our satellite monitoring program revealed that wolves were migratory, just like caribou, with most packs tracking the movements of caribou, at least from late summer to the spring.
- Black bears appear to concentrate on the calving grounds of the Rivière-George herd and consume caribou calves daily.

OBJECTIVES

1. To determine life-history variation in known-age individuals, more specifically to assess longitudinally age-specific survival and reproduction of radio-collared animals (PhD 1 – J. Taillon, MSc 1 – M. Pachkowski, MSc 5 – A. Rasiulis; Collaborators – V. Brodeur and S. Couturier).
2. To analyze habitat selection of migratory caribou at different scales in all seasons, in particular in relation to migration routes and anthropogenic disturbance. To continue modeling the effects of climate change on the distribution of caribou. To use remote sensing tools to link changes in vegetation phenology and movements of caribou. To evaluate the extent to which inter-annual variation in the range use of migratory caribou can be explained by demographic trends and spatiotemporal changes in forage availability (PhD 2 – M. Le Corre, PhD 3 – B. Dalziel, PhD 6 – S. Plante, MSc 7 – B.A. Campeau).
3. To determine the influence of past and future climate change on genetic diversity in caribou/reindeer populations throughout their circumpolar distribution. To assess the conservation units of caribou in Québec and Labrador. To test the ability of habitat selection to predict genetic relatedness among caribou (Post-doc 1

– G. Yannic; Collaborators – L. Bernatchez, K. Røed, K. Hundertmark, D. Paetkau, C. Cuyler, M. Musiani, D. Jenkins, M. Kholodova, M.-H. St-Laurent).

4. To study the impact of parasites (e.g. *Besnoitia*, liver flukes) on the ecology of caribou. To compare parasite diversity and abundance in caribou from Quebec with those from elsewhere in the Arctic (MSc 2 – J. Ducrocq, MSc 6 – Alice-Anne Simard; Collaborators – S. Kutz, B. Elkin, S. Lair).
5. To understand the relationships between the grazing ecology of caribou and short and long term effects of climate change on the summer range of caribou (MSc 3 – E. Champagne, MSc 4 – V. Saucier; Collaborators – E. Lévesque, L. Hermanutz, P. Grogan).
6. To study the impact of predation by wolves and black bears on the population dynamics of caribou by initiating a large-scale monitoring program of predators using satellite collars (PhD 4– to be determined, PhD 5 – to be determined).

INTRODUCTION

Migratory caribou (*Rangifer tarandus*) are central to the ecology of northern areas and are at the heart of this region's culture and economy. Despite major monitoring and research efforts, caribou remain poorly known, making their management problematic. Most caribou populations have witnessed major variations in their abundance in the past and their numbers are still changing today (Vors and Boyce 2009). Climate change will likely have multiple effects on the northern habitats of migratory caribou. For example, more snow or rain in late winter could compromise movements and foraging behaviour (Weladji and Holand 2003, Tyler 2010). A milder climate will shorten the period when hydroelectric reservoirs are frozen, which could influence the timing of migration, the choice of migratory routes and even increase the risk of mass drownings. These expected effects could have repercussions on the energy balance and survival of animals as well as on dispersal among populations (Boulet et al. 2007). Changes in the spring phenology of plants (Post and Stenseth 1999) could lead to a phase shift between the period of abundance of high-quality food and the peak of lactation (Pettorelli et al. 2007). Given the scope of anticipated climate change, there is much concern about its potential effects on caribou and on the interactions between plants and caribou.

Several major hydroelectric and mining projects have been developed within the habitat of migratory caribou in Québec and Labrador (Jean and Lamontagne 2005), and a lot more are planned. The cumulative effects of human disturbance may reduce the availability or quality of essential habitats such as calving grounds (Johnson et al. 2005, Taillon et al. 2012). Assessing the impact of human activities on caribou space use and caribou habitat as well as on the choice of migratory routes is essential to understand its population dynamics (Bolger et al. 2008).

A decrease in the abundance and distribution of caribou could have negative repercussions on Aboriginal Peoples and on the outfitting industry of Northern Québec and Labrador. The recent decline of the Rivière-George herd raised questions about the sustainability of sport and subsistence harvest on this herd. Therefore, greater knowledge of population dynamics is needed to ensure the conservation of this resource. A long-term research program is essential to improve the management and conservation of migratory caribou. Several characteristics of caribou (long life expectancy, reproduction over 5 to 10 years, influence of age on reproduction and survival rates) necessarily imply major temporal variations in the dynamics of populations. To understand the impact of factors that are dependent and independent of density (e.g. climate factors), it is necessary to analyze a long time series covering a wide range of conditions.

We concentrate our research on the two large herds of migratory caribou in northern Québec and Labrador, the Rivière-George and Rivière-aux-Feuilles herds. These populations have been monitored for >20 years through satellite collars by the Ministère du Développement durable, de l'Environnement, de la Faune et des Parcs du Québec (MDDEFP; formely the Ministère des Ressources naturelles et de la Faune, MRNF), a major partner in our research program, and more recently by Caribou Ungava. Both herds are central to the economy and traditional life of northern peoples. The future demography of migratory caribou facing climate change and industrial development of the North is essential to understand in the context of the Integrated Regional Impact Studies of ArcticNet and the continuing development of northern Quebec and Labrador.

ACTIVITIES

Fieldwork activities

- March 2014 – Two field trips were made in order to increase the number of satellite collars on male caribou from the Rivière-George and Rivière-aux-Feuilles herds in anticipation of the 2014 summer surveys. We captured 16 and 19 new caribou respectively from the Rivière-aux-Feuilles and Rivière-George herds, and fitted them with satellite collars. We also replaced collars nearing the end of their battery life on 2 others and recovered 4 radio-collars from dead caribou. Finally, 2 collars were installed on wolves. This fieldwork was conducted in partnership with the MFFP and the government of Newfoundland.
- June 2014 – Two teams were simultaneously in the field to capture caribou, wolves and black bears on Rivière-aux-Feuilles and Rivière-George calving grounds. We captured and fit with new satellite collars 12 and 11 female yearlings from the Rivière-George and the Rivière-aux-Feuilles herds, respectively. We also captured 6 adult females of known age from the Rivière-aux-Feuilles herd and replaced the collar of three others. Six and 13 collars from dead caribou were recovered for the Rivière-aux-Feuilles and Rivière-George herds, respectively. One black bear from the Rivière-aux-Feuilles herd range and 4 black bears from the Rivière-George herd range were fitted with satellite collars. Collars have been replaced on 8 bears from the Rivière-George herd range and the lost collars of two wolves and one bear from the Rivière-aux-Feuilles herd range were recovered. We conducted fieldwork in partnership with the MFFP and the Government of Labrador.
- June to August 2014 – Fieldwork for the vegetation and climate experiments at Deception Bay, conducted in partnership with Xstrata – Mine Raglan.
- October 2014 – We continued the monitoring of reproductive success of radiocollared female caribou (calf presence/absence) from the Rivière-aux-Feuilles and Rivière-George herds. We conducted the classification of more than 3000 individuals and performed a recruitment survey. We conducted fieldwork in partnership with the MFFP and Government of Labrador.

Meetings, conferences and workshops

- May 2014 – We held a spring meeting of the scientific committee of the caribou project to plan fieldwork activities for the summer.
- Spring, Summer and Autumn 2014 – We presented our results at many occasions such as the the 15th North American Caribou Workshop, Aminor workshop in Tromsø, Norway, the University of Wyoming, the annual meeting of the Association des Biologistes du Québec, the annual conference of the biology department of Université Laval, the Northern Studies Centre in Kuujjuarapik and their annual meeting in

Quebec City, the 39th Annual meeting of the Société Québécoise pour l'Étude Biologique du Comportement, the annual conference of the Canadian Section of the Wildlife Society, the Ouranos symposium, and the 10th ArcticNet annual scientific meeting.

RESULTS

Objective 1. To determine life-history variation in known-age individuals, more specifically to assess longitudinally age-specific survival and reproduction of radio-collared animals.

1.1 - 1.2 - 1.3: Our results concerning the effects of maternal characteristics on juvenile mass, size and fat storage on conception probability, and on the effects of population size on maternal phenotype and fat reserves were presented in our last reports. Most of those results are published in:

- Taillon, J., P. S. Barboza and S. D. Côté. 2013. Nitrogen allocation to offspring and milk production in a capital breeder. Ecology 94: 1815-1827.
- Taillon, J., V. Brodeur, M. Festa-Bianchet and S. D Côté. 2012. Is mother condition related to offspring condition in migratory caribou at calving and weaning? Canadian Journal of Zoology 90: 393-402.
- Taillon, J., V. Brodeur, M. Festa-Bianchet and S. D Côté. 2011. Variation in body condition of migratory caribou at calving and weaning – which measures should we use? Ecoscience 18: 295-303.
- Pachkowski, M. D., S. D. Côté and M. Festa-Bianchet. 2013. Spring-loaded reproduction: effects of body condition and population size on fertility in migratory caribou (*Rangifer tarandus*). Canadian Journal of Zoology 91: 473-479.

1.4: Information on demographic parameters such as survival and reproduction is central to understand population dynamics (Lebreton et al. 1992, Sandercock 2006). Although changes in fecundity and recruitment rates may have a substantial impact on population growth (Blakesley et al. 2010), any changes in adult survival rates in long-lived species can become key drivers of temporal variation in population size (Gaillard et al. 2000, Sæther and Bakke 2000). Using data from long-term satellite monitoring of migratory caribou, we sought to evaluate the survival rate of adults from both herds in Quebec-Labrador and assess environmental factors influencing survival. First, we evaluated the effect of radio-collar weight on survival of migratory caribou from the Rivière-George herd. We compared survival of adult females (2 years old) wearing a light very high frequency (VHF) collar (514 g) to that of females wearing a heavy satellite collar (1.63 kg) over 5 years. Females equipped with VHF collars had much higher annual survival rates (86%; $\hat{c} < 1$, SD = 9.79) than females with satellite collars (68.4%; $\hat{c} < 1$, SD = 5.78; Figure 1) between 1991 and 1994 and in 2000. These results are now published in:

- Rasiulis, A. L., M. Festa-Bianchet, S. Couturier and S. D. Côté. 2014. The effect of radio-collar weight on survival of migratory caribou. The Journal of Wildlife Management 78:953-956.

1.5: Our major results concerning the protection of caribou calving grounds were presented in our last reports and are published in:

- Taillon, J., M. Festa-Bianchet and S. D. Côté. 2012. Shifting targets in the tundra: protection of migratory caribou calving grounds must account for spatial changes over time. Biological Conservation 147:163-173.

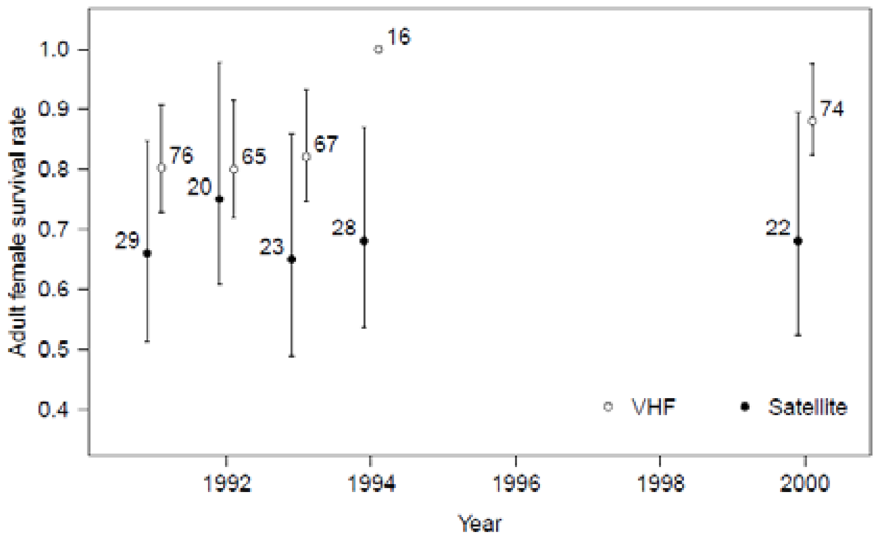

Figure 1. Annual survival rates with 95% confidence intervals of adult female caribou from the Rivière-George herd equipped with either light very high frequency (VHF) or heavy satellite collars (Argos) between 1991 and 2000. The number of individuals is indicated for each year. From Rasiulis et al. 2014. © 2014, John Wiley and Sons. © The Wildlife Society, 2014.

Objective 2. To analyze habitat selection by migratory caribou at different scales in all seasons, in particular in relation to migration routes and anthropogenic disturbance. To continue modeling the effects of climate change on the distribution of caribou. To use remote sensing tools to link changes in vegetation phenology and movements of caribou. To evaluate the extent to which inter-annual variation in the range use of migratory caribou can be explained by demographic trends and spatiotemporal changes in forage availability.

2.1: Migratory species face numerous threats related to human encroachment and climate change. Several migratory populations are declining and individuals in certain circumstances are losing their migratory behaviour. To understand how habitat loss or changes in the phenology of natural processes affect migrations, it is crucial to identify the timing and patterns of migration. We propose an objective method, based on the detection of changes in movement patterns, to identify departure and arrival dates of the migration. We tested the efficiency of our approach using simulated paths before applying it to spring migration of migratory caribou from the Rivière-George and Rivière-aux-Feuilles herds in northern Québec and Labrador. We applied the First-Passage Time analysis (FPT) to locations of 402 females collected between 1986 and 2012 to characterize their movements throughout the year. We then applied a signal segmentation process in order to segment the path of FPT values into homogeneous bouts to discriminate migration from seasonal range use. This segmentation process was used to detect the winter break and calving ground use because spring migration is defined by the departure from the winter range and the arrival on the calving ground. Segmentation of the simulated paths was successful in 96% of the cases, and had a high precision (96.4% of the locations assigned to the appropriate segment). We detected 100% of the expected winter breaks and 89% of the expected calving ground use, and identified 648 complete spring migrations among the 813 winter breaks and 669 calving ground use expected to be detected on the FPT profiles, and assuming that individuals always reduced movements for each of the two periods. Failures to segment winter breaks or calving ground use were related to a few individuals only slowing down or performing less pronounced pauses resulting in low mean FPT. Results are now published in:

- Le Corre, M., C. Dussault and S. D. Côté. 2014. Detecting changes in the annual movements of migratory caribou: using the first-passage time to assess departure and arrival of the spring migration. Movement Ecology 2:19.

Patterns of migration as well as departure and arrival dates assessed with our segmentation method were used respectively in section 2.2 and section 2.3.

2.2: Migratory species are actually facing changes in their habitat mainly due to climate change, particularly in northern environments where changes appear to be more drastic (Graversen et al. 2008). Climate change could affect migrant species through changes in the phenology of natural processes (Parmesan and Yohe 2003), but also through loss or changes in the distribution of suiTable habitats (Moore et al. 2003, Sanderson et al. 2006, Yannic et al. 2014). During the last decades, migratory caribou from the Rivière-George and Rivière-aux-Feuilles herds have shown variation in the use of their winter ranges (Schaefer et al. 2000, Couturier et al. 2009b), leading to different migration patterns. Our objective was to assess how climate conditions encountered during fall migration, resources and population size affect the fall migration patterns.

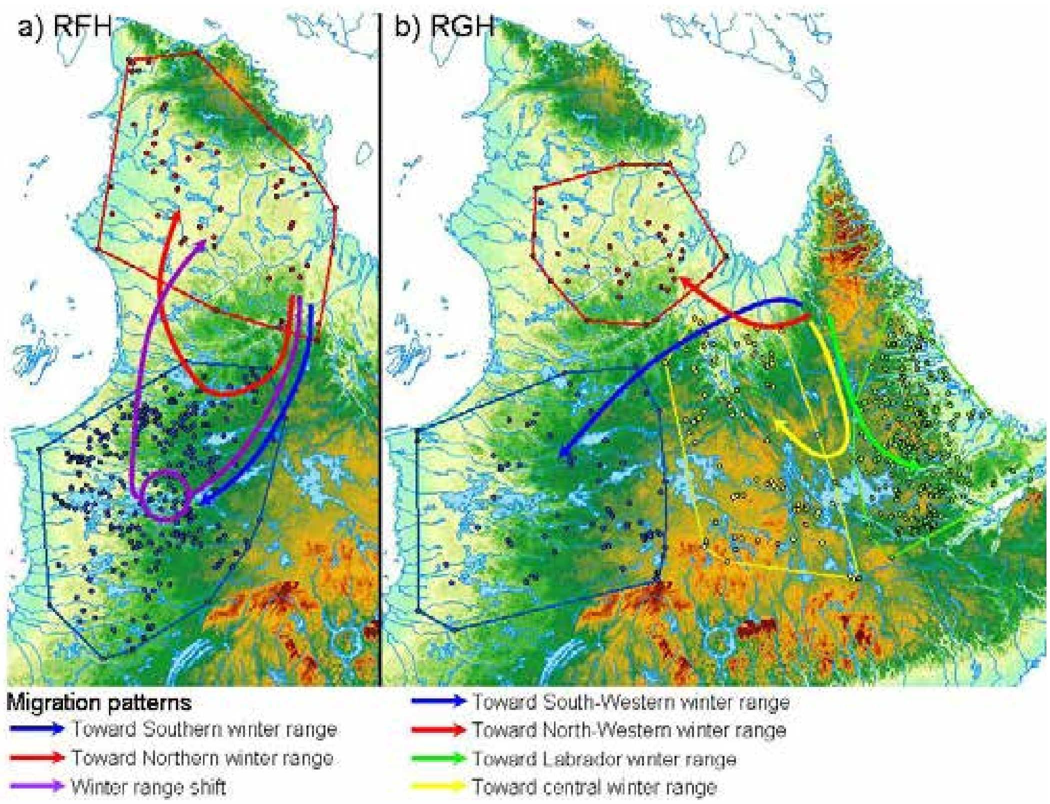

Figure 2. Fall migration patterns of a) the Rivière-aux-Feuilles herd (RFH) and b) the Rivière-George herd (RGH). Winter ranges were assessed by a cluster analysis performed on the centroid of the winter break of each individual and are represented by the Minimum Convex Polygon of these clusters.

Three patterns of migration can be observed during fall for the Rivière-aux-Feuilles herd (Figure 2a): a main migration toward a southern winter range located in the taïga, a migration toward a northern winter range located in the tundra, and an intermediate pattern with individuals migrating toward the southern winter range then shifting to the northern winter range at the end of January (referred to as winter range shift hereafter). Four patterns of migration can be observed for the Rivière-George herd (Figure 2b): a main migration toward Labrador, a migration toward a central winter range, and two migrations toward the north-western and south-western winter ranges, overlapping the Rivière-aux-Feuilles herd winter ranges. We used the North Atlantic Oscillation Index (NAO) to describe climate at a large scale (Hurrell 1995). At a finer scale we used monthly climate data (temperatures, precipitations, snow water equivalent) from the Canadian Regional Climate Model (CRCM v4.3, res: 45 km) produced by Ouranos (de Elía and Côté 2010). We used Normalized Difference Vegetation Index (NDVI) data to describe plant productivity (Couturier et al. 2009b). Finally we took into account the variations in population size of the two herds. In order to assess which variables affect the probability to observe the different patterns of fall migration we used a classification procedure, the random forests analysis (Breiman 2001). Random forests allow the identification of variables that influence the most the classification by looking at their statistical effect size. The effect size here is assessed by the mean decrease in the classification accuracy when the variable is altered by randomly permuting the values of the variable. A steeper decrease in accuracy indicates that the variable has a large influence to the classification (Figure 3). Once the most influential variables were identified, we used multinomial regression to assess their effect on the probability to observe the different patterns of fall migration.

The most influential variables in the probability to observe the different migration patterns for the Rivière-aux-Feuilles herd were the population size of the Rivière-George herd, the population size of the Rivière-aux-Feuilles herd, precipitations and the snow water equivalent in November (Figure 3). Multinomial regression indicated that the probability to observe migrations toward the southern winter range increased as the population size of the Rivière-George herd decreased and probability to observe migrations toward the northern winter range or winter range shifts was high when the Rivière-George population was high (Figure 4a). Probability to observe winter range shifts also increased as the Rivière-aux-Feuilles population increased (Figure 4b) but decreased if individuals encountered abundant snow during the migration (Figure 4d). Despite random forests identified precipitations in November as a potentially influential variable we did not detect any effect on the probability to observe the different migration patterns. For the Rivière-George herd, due to the low number of observed migrations toward the north-western winter range, we included in the multinomial regression the three most influential

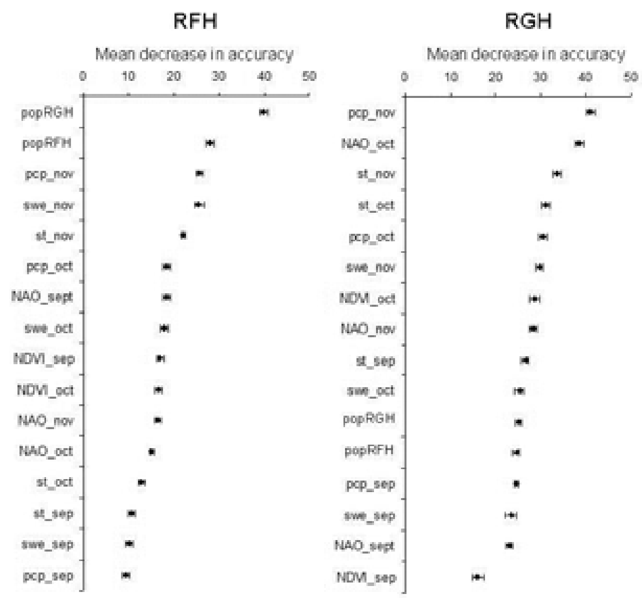

Figure 3. Variable importance with SD from random forest classifications used for predicting winter range use of the Rivière-aux-Feuilles herd (RFH) and the Rivière-George herd (RGH) represented by the mean decrease in the accuracy of the classification when the variable is altered. swe: snow water equivalent; sc: snow cover; ic: ice cover; st: surface temperatures; pcp: precipitations; popRGH/RFH: herd population size.

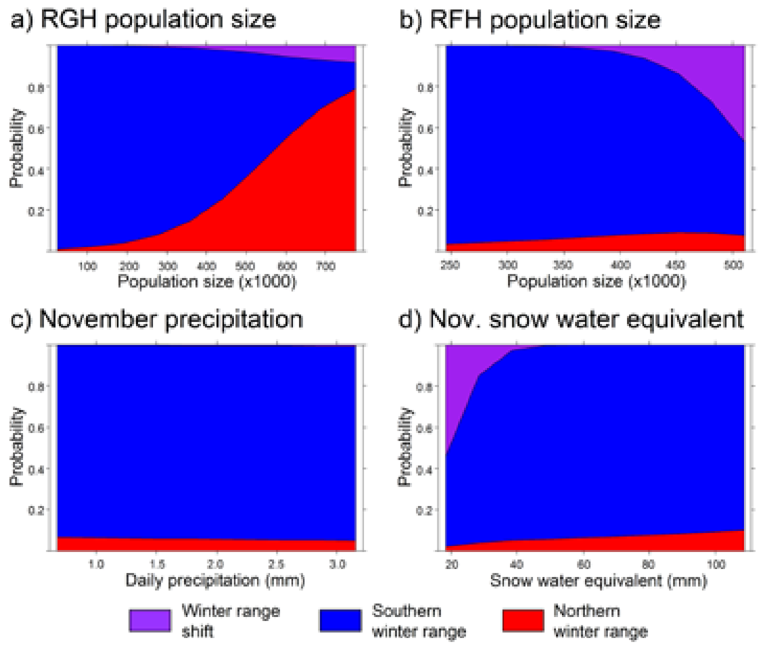

Figure 4. Cumulative probabilities to observe migration toward the Southern winter range (blue), migration toward the Northern winter range (red) and winter range shift (purple) for the Rivière-aux-Feuilles herd according a) the Rivière-George herd population size, b) the Rivière-aux-Feuilles herd population size, c) the November daily precipitation, d) the November snow water equivalent.

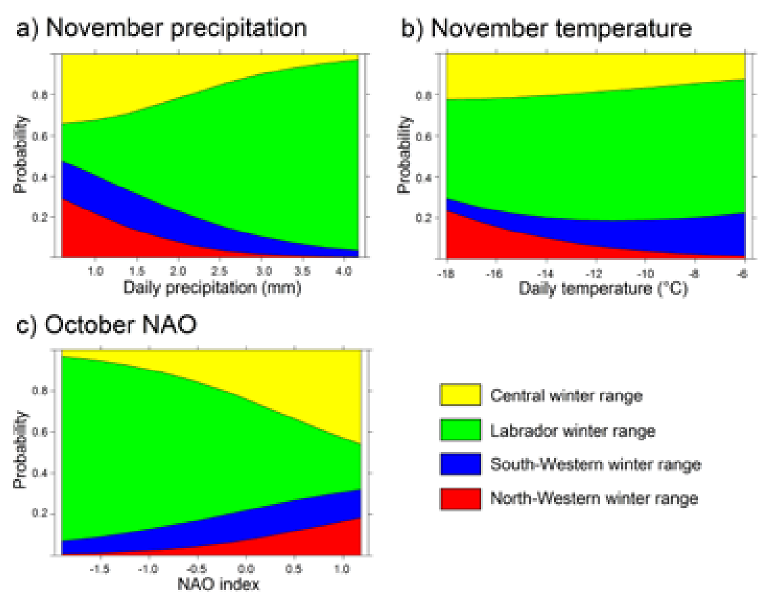

Figure 5. Cumulative probabilities to observe migration toward the South-Western winter range (blue), the North-Western winter range (red), the central winter range (yellow) and the Labrador winter range (green) for the Rivière-George herd according to a) November daily precipitation, b) November temperature, c) October NAO.

variables assessed by the random forests (Figure 3). Caribou were more prone to migrate toward the Labrador winter range when they encountered abundant precipitations during their migration as shown by the effect of the November precipitations (Figure 5a) and the October NAO (Figure 5c), positive values of NAO corresponding to dry and cold climate. Conversely, caribou were more prone to use central and particularly north-western winter ranges when precipitations and temperatures in November were low (Figures 5a, b) and values of NAO in October were positive (Figure 5c).

2.3: Synchrony between the timing of migration and resource availability is fundamental to the survival of many migrant species (Møller et al. 2008, Post and Forchhammer 2008). However, the timing of environmental processes is changing under global climate changes (Parmesan and Yohe 2003). Thus, it is essential to understand how climate change affects the different phases of migration to estimate their global impact on migrant species. Our objective was to study the impact of local and global climate and of availability of food resources on the timing of the spring and fall migrations of migratory caribou from the two herds.

We investigated the effect of snow and ice cover, temperature, precipitations, broad scale climatic variations (e.g., NAO), and resource abundance on the departure and arrival dates of the spring and fall migrations. We also considered population size because it can affect the timing of migration (Hinkes et al. 2005). We used the locations of 120 females for the Rivière-George herd and 116 females for the Rivière-aux-Feuilles herd between January 2000 and December 2011. Among the 377 spring migrations made by 178 females, we obtained 372 departure dates and 354 arrival dates. Among the 499 fall migrations made by 230 females, we obtained 464 departure dates

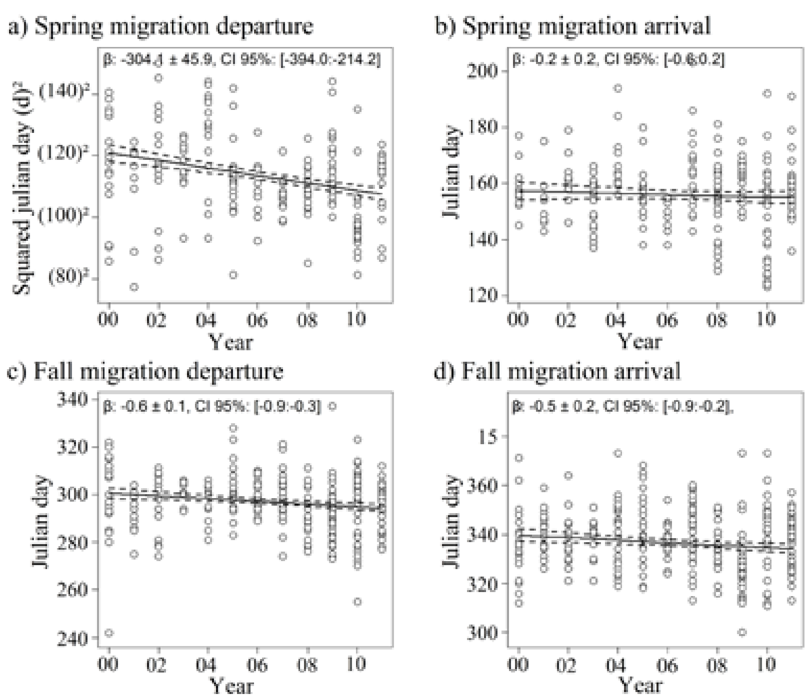

Figure 6. Changes in migration phenology of migratory caribou from northern Québec and Labrador between 2000 and 2011 with fitted trends and 95% confidence interval (dashed lines). a) Spring migration departure (dates in squared Julian days); b) Spring migration arrival; c) Fall migration departure; d) Fall migration arrival. Estimates are given with their standard error and 95% confidence interval.

Table 1. Variables used to investigate changes in the phenology of the spring and fall migrations of the Rivière-aux-Feuilles and Rivière-George migratory caribou herds. For each variable, we indicated the time period over which we averaged the data.

	Spring migration departure		Spring migration arrival		Fall migration departure		Fall migration arrival	
Variable category	Selected variables	Effects	Selected variables	Effects	Selected variables	Effects	Selected variables	Effects
Snow and ice cover	swe_wint	NS	swe_may	NS	**swe_sept**	+	**swe_nov**	-
			sc_may	NS	sc_sept	NS	sc_nov	NS
			ic_may	NS	ic_sept	NS	ic_nov	NS
			swe_june	+	sc_oct	NS	swe_dec	NS
			sc_june	NS	ic_oct	NS	sc_dec	NS
			ic_june	NS			ic_dec	NS
Local climate	**st_wint**	-	**st_may**	+	st_sept	NS	**st_nov**	-
	pcp_wint	NS	**pcp_may**	+	pcp_sept	NS	pcp_nov	NS
	st_apr	NS	st_june	NS	st_oct	NS	**st_dec**	+
	pcp_apr	+	pcp_june	NS	**pcp_oct**	-	pcp_dec	NS
Global climate							**NAO_nov**	-
							NAO_dec	+
Vegetation			NDVI_june	NS	NDVI_sept	NS		NS
					NDVI_oct	-		NS
Herd characteristics	**Herd ID**	-	**Herd ID**	+	**Herd ID**	-	Herd ID	NS
	pop_size	+	pop_size	NS	pop_size	NS	**pop_size**	+

Table 2. Effects of the variables on migration phases from the best model explaining variations in a) the departure date and b) the arrival date of the spring migration, and c) the departure date and d) the arrival date of the fall migration. Results are from linear mixed models with female identity as a random factor.

Migration phase	Period over which data were averaged	Variable category				
		Snow and ice	Local climate	Global climate	Vegetation	Herd characteristics
Spring departure	Winter (January-March)	swe	st + pcp	NAO	-	Herd ID + pop_size
	April	swe	st + pcp	NAO	-	
Spring arrival	May	sc + ic + swe	st + pcp	NAO	-	Herd ID + pop_size
	June	sc + ic + swe	st + pcp	NAO	NDVI	
Fall departure	September	sc + ic + swe	st + pcp	NAO	NDVI	Herd ID + pop_size
	October	sc + ic + swe	st + pcp	NAO	NDVI	
Fall arrival	November	sc + ic + swe	st + pcp	NAO	-	Herd ID + pop_size
	December	sc + ic + swe	st + pcp	NAO	-	

and 471 arrival dates. We used the global and local climate data, NDVI and demographic data described in section 2.2. We also used snow and ice cover data from MODIS imagery (res: 0.5 km; Hall et al. 2006). For each migration phase, we tested the effect of climate and environmental variables measured during the month for which most of the departures or arrivals occurred, as well as those measured during the preceding month (Table 1).

During the 12-year study period, migratory caribou significantly advanced their departure from the winter range and the summer range and arrived earlier, at fall, on the winter range (Figures 6a, c, d). Only the arrival date on the calving ground has not significantly changed (Figure 6b). Selected variables for the different migration phases are presented in Table 2. The sign of the effect of a variable on the departure or arrival dates is indicated when the effect is significant. We observed differences between herds as females from the Rivière-aux-Feuilles herd departed earlier than females from the Rivière-George herd during spring and fall and arrived later on their calving ground. Spring departure occurred earlier at low population size and in years with mild winter temperatures (Figure 7a). Departure was delayed in years with abundant precipitations in April. Spring arrival date was delayed in years when caribou faced abundant precipitations and warm temperatures during migration (Figure 7b), and when snow was abundant upon arrival on the calving grounds. In the fall, departure date was delayed in years when snow water equivalent was high in September, when there was little precipitations in October, and when October NDVI values were low (Figure 7c). Caribou terminated their fall migration sooner in years when snow water equivalent was high in November. Relatively cold November temperatures resulted in late arrivals (Figure 7d), whereas mild December temperatures resulted in early arrivals on wintering grounds. Finally, fall arrival was negatively related with NAO in November and positively related with NAO in December.

2.4: An analysis of the space use patterns of satellite-collared Rivière-George caribou has shown large changes in the space use of females during the calving period (Taillon et al. 2012), with probable linkages to caribou demographic trends and changes in green forage availability. From 1991 to 2000, a period

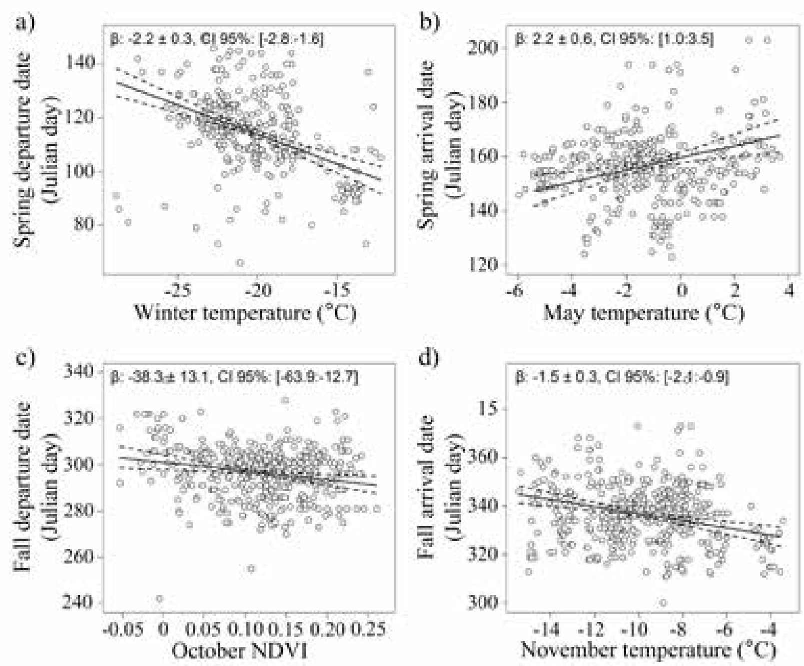

Figure 7. Relationship with fitted trends and 95% confidence interval (dashed lines) between a) the spring migration departure date and the mean daily temperature for the entire winter (January to March), b) the spring migration arrival date and the mean daily temperature in May, c) the fall migration departure date and the mean NDVI value in October and d) the fall migration arrival date and the mean daily temperature in November. Estimates are given with their standard error and 95% confidence interval.

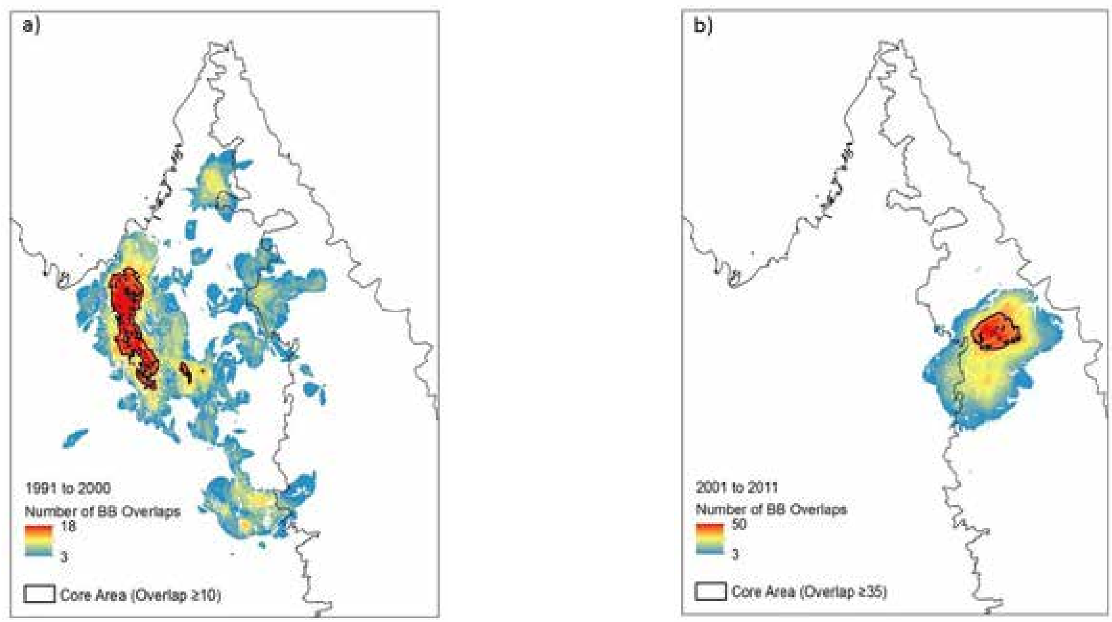

Figure 8. The distribution of the Rivière-George caribou herd in Northern Québec and Labrador during the calving period for 1991-2000 (a) and 2001-2011 (b), based on the annual Brownian Bridge (BB) 95% home ranges of all collared females determined to have reached the calving grounds using First-Passage Time analysis; core areas were identified for each time period based on the extent of BB overlap; the 1991-2000 period includes home ranges from 166 caribou-years and uses a core area threshold of ≥10 BBs, whereas the 2001 to 2011 period includes home ranges from 140 caribou-years and uses a core area threshold of ≥35 BBs; note that areas with <3 BB overlaps are excluded from the map; white areas within clusters represent water bodies.

with 166 caribou-years of location data, females ranged across a large area between Ungava Bay and the Torngat Mountains on the Labrador Peninsula, showing little site fidelity to specific areas; this period coincides with the collapse in the Rivière-George herd population size from 823,000 (1993, aerial census data) to ca. 171,000 (2000, modelled data) (Rasiulis 2015). From 2001 to 2011, a period with 140 caribou-years of location data, females showed much stronger site fidelity to a relatively small area on the east side of the Torngat Mountains, near the Atlantic coast; this period is marked by low population size, showing a decrease from 385,000 (2001, aerial census data) to ca. 61,000 (2011, modelled data) (Rasiulis 2015). The core areas that characterize each of these two time periods are very distinct and reflect a clear shift in calving grounds use around the year 2000 (Figure 8).

The two core areas are very different in terms of their predominant environmental characteristics. The 1991-2000 core area lies at a lower mean elevation than the 2001-2011 core area (205 m and 447 m, respectively) and it shows less topographic variability (standard deviation: 88 m and 121 m, respectively). There are also clear differences in vegetation productivity between the two core areas, as seen in the temporal trend in growing season length and cumulative growing season NDVI (cNDVI) (Figure 9). The 1991-2000 core area has a longer growing season and higher primary productivity. Growing season length is highly variable for both core areas, but there appears to be a subtle trend towards longer growing seasons over the last two decades. The positive trend in cNDVI is more pronounced, especially for the 1991-2000 core area. The trends in

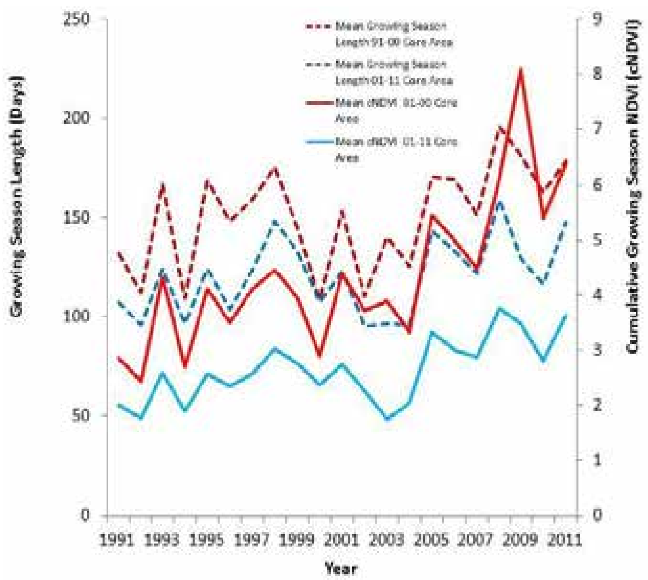

Figure 9. Inter-annual changes in mean growing season length (dashed lines) and mean cumulative growing season NDVI (cNDVI, solid lines) in the two core areas (delimited in Figure 8), the 1991-2000 core area (red) and the 2001-2011 core area (blue).

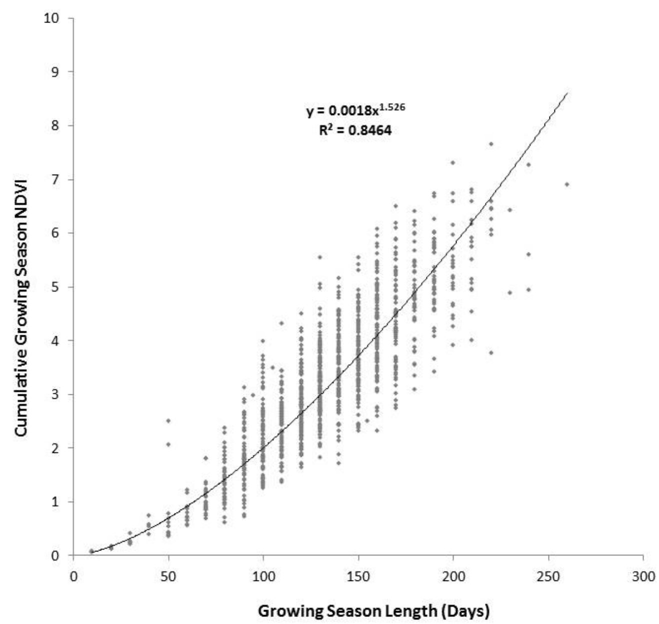

Figure 10. The power function used to model the relationship between cumulative growing season NDVI (cNDVI) and growing season length for the global 1991-2011 Rivière-George calving grounds; the points represent data from over 1,000 1 km² AVHRR pixels that were randomly selected from the global calving grounds, with 40 pixels selected for each year of the AVHRR record (1984-2011); 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.

cNDVI closely follow the trends in growing season length.

The relationship between cNDVI and growing season length can be modelled using a simple power function (Figure 10). This model explains much of the observed variation in cNDVI in the global 1991-2011 Rivière-George calving grounds over the 1984-2011 period for which NDVI data are available ($R^2 = 0.85$). The residuals from this 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.

The relationship between mean model residuals and estimates of caribou density during the calving period, an index of caribou foraging and trampling pressure, was investigated for the two core areas using data from all of the years used to define the core areas (Figure 11). The relationship proved strongest when considering caribou density with a 1-year lag relative to the model residual data. However, a significant relationship was only identified for the 1991-2000 core area; the model residuals are negatively correlated with lagged caribou density ($t = -2.61$, $\alpha = 0.05$, P-value = 0.0328). A negative relationship was also predicted for the 2001-2011 core area, but no significant relationship was identified ($t = 1.97$, P-value = 0.0877).

When considering the temporal nature of the relationship between model residuals and lagged caribou density, there appears to be some influence of caribou presence/absence on primary productivity, but only for the 1991-2000 core area (Figure 12). In this area, the mean model residuals are significantly more positive during the period when caribou are absent (2002-2011) than during the earlier period when caribou are present (1992-2001) ($t = 3.49$, P-value = 0.0040). For the 2001-2011 core area, however, there is

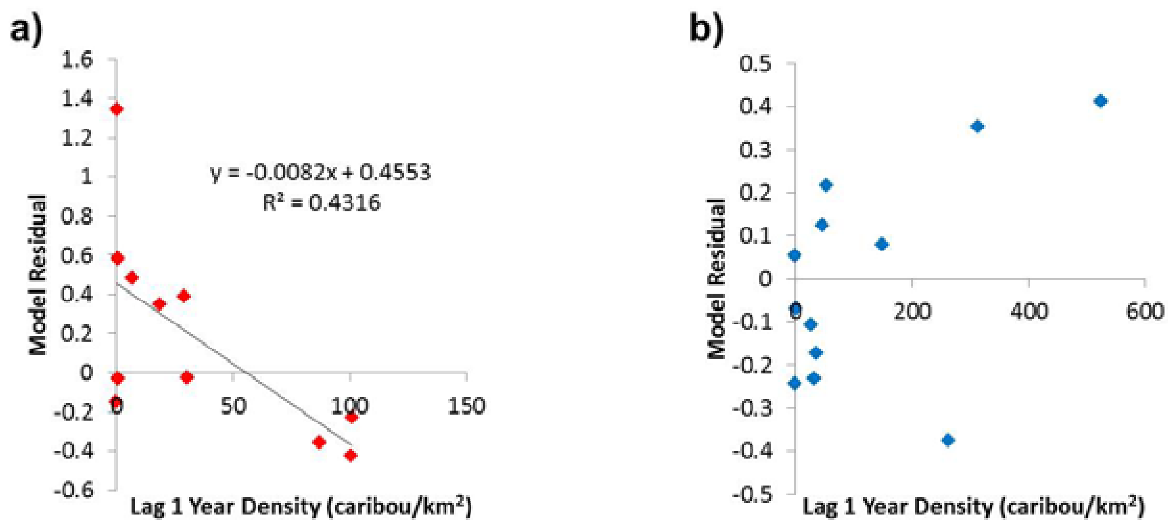

Figure 11. For the 1991-2000 core area (a) and the 2001-2011 core area (b), the mean model residuals from the NDVI-climate model (Figure 10) are plotted against estimates of caribou density, lagged by 1 year, from within the core area during the calving period; each point therefore represents the mean model residual for year x and caribou density for year x – 1, for all years used to define the core area; there is a significant negative relationship for the 1991-2000 core area (t=-2.61, p=0.03), but no significant relationship for the 2001-2011 core area (t=1.97, p=0.09).

no significant difference in mean model residuals between the period of caribou presence (2002-2011) and the earlier period of caribou absence (1991-2001) (t=-2.00, P=0.06).

Objective 3. To determine the influence of past and future climate change on genetic diversity in caribou/reindeer populations throughout their circumpolar distribution. To assess the conservation units of caribou in Québec and Labrador. To test the ability of habitat selection to predict genetic relatedness among caribou.

3.1: Climate-driven range fluctuations during the Pleistocene have continuously reshaped species distribution leading to populations of contrasting genetic diversity. Contemporary climate change is similarly influencing species distribution and population structure, with important consequences for patterns of genetic diversity and species' evolutionary potential (Parmesan 2006). Yet few studies assessed the impacts of global climate changes on intraspecific genetic variation (Rubidge et al. 2012, Pauls et al. 2013). Combining analyses of molecular data with time series of predicted species distributions and a model of diffusion through time over the past 21 kyr, we unraveled caribou response to past and future climate changes across its entire Holarctic distribution. We found that genetic diversity is geographically structured with two main caribou lineages, one originating from and confined to Northeastern America, the other originating from Euro-Beringia but also currently distributed in western North America. Regions that remained climatically sTable over the past 21 kyr maintained a high genetic diversity and are also predicted to experience higher climatic stability under future climate change scenarios. The detailed results of this study are presented in our last report and are now published in:

- Yannic, G., L. Pellissier, J. Ortego, N. Lecomte, S. Couturier, C. Cuyler, C. Dussault, K. J. Hundermark, R. J. Irvine, D. A. Jenkins, L. Kolpashikov, K. Mager, M. Musiani, K. L. Parker, K. H. Roed, T. Sipko, S. G. Þórisson, B. V. Weckworth, A. Guisan, L. Bernatchez and S. D. Côté. 2014. Genetic diversity in caribou linked

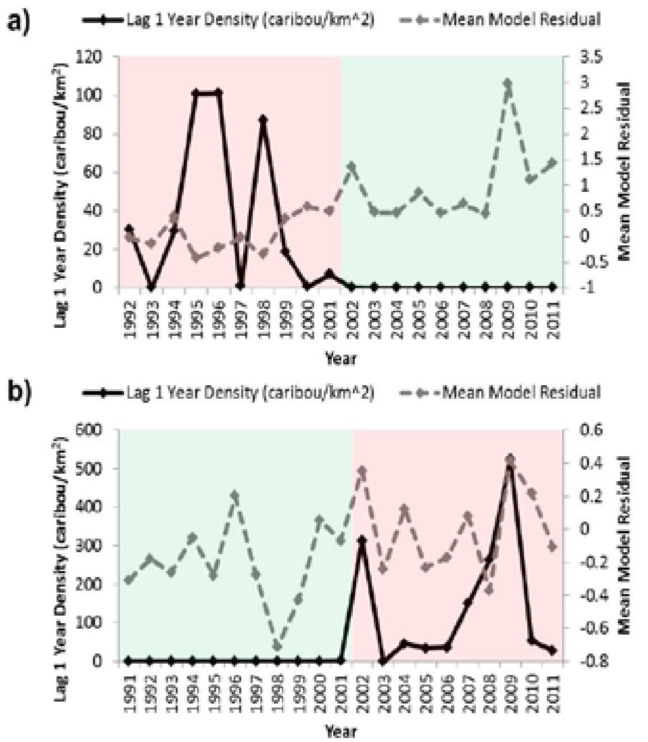

Figure 12. Inter-annual changes in mean model residuals and estimates of caribou density, with a 1-year lag, for the two core areas (delimited in figure 8), the 1991-2000 core area (a) and the 2001-2011 core area (b); the time series are separated into two periods based on the density estimates: caribou present (light red) and caribou absent (light green); for the 1991-2000 core area, mean model residuals are significantly different between the two periods, with mean model residuals being more positive when caribou are absent (t=3.49, p=0.004); there is no significant difference in mean model residuals between the two periods for the 2001-2011 core area (t=-2.00, p=0.06).

to past and future climate change. Nature Climate Change 4:132-137.

<u>3.2:</u> Identifying conservation units (CUs) below the species level is becoming increasingly important, particularly when limited resources require focusing conservation efforts on some particular units or populations. Among the criteria used to delineate CUs, the amount of intra-specific genetic variation is now widely accepted as a key parameter to determine populations. Many animal species also harbour ecological characteristics (e.g. behaviour, habitat use, etc.) that may reflect potential adaptation to local environmental conditions (i.e., ecotypes). Genetic and ecological data provide complementary information that should be integrated to make optimal conservation decisions. We proposed a framework based on genetic information and ecological criteria - primarily ecotype designation - to define conservation units in caribou from Québec and Labrador. The major results of this study are presented in our last report and a manuscript is currently under review:

- Yannic, G., M.-H. St-Laurent, J. Taillon, J. Ortego, A. Beauchemin, C. Dussault and S. D. Côté. Defining management units at the landscape scale: the ecological and genetic structure of caribou populations. Journal of Mammalogy, submitted.

<u>3.3:</u> Landscape heterogeneity plays a central role in shaping ecological and evolutionary processes. While species utilization of the landscape is usually viewed as constant within a year, the spatial distribution of individuals is likely to vary in time in relation to particular seasonal needs. Understanding temporal variation in landscape use and genetic connectivity has direct conservation implications. We modelled the daily use of the landscape by caribou in Quebec and Labrador, and tested its ability to explain the genetic relatedness among individuals. We assessed habitat selection using locations of collared individuals in migratory herds and static occurrences from sedentary groups. Connectivity models based on habitat use outperformed a baseline isolation-by-distance model in explaining genetic relatedness, suggesting that variations in landscape features such as snow, vegetation productivity and land use modulate connectivity among populations. Connectivity surfaces derived from habitat use were the best predictors of genetic relatedness. The relationship between connectivity surface and genetic relatedness varied in time and peaked during the rutting period. Landscape permeability in the period of mate searching is especially important to allow gene flow among

populations. The major results are presented in our last report and are now published in:

- Yannic, G., L. Pellissier, M. Le Corre, C. Dussault, L. Bernatchez and S. D. Côté. 2014. Temporally dynamic habitat suitability predicts genetic relatedness among caribou. Proceedings of the Royal Society 281:20140502.

3.4: Delineating the genetic basis of neutral and adaptive divergence of populations is a long-standing goal in ecology and evolution. When populations experience different environments, local divergent selection pressures can result in phenotypic differentiation in traits that confer a local fitness advantage (Kawecki and Ebert 2004, Rundle and Nosil 2005, Shafer and Wolf 2013). Understanding the mechanisms that allow individuals to adapt to their native environment is essential, given that local adaptation may strongly impact how species respond to global changes, thus having direct evolutionary and conservation implications (Fraser and Bernatchez 2001, Funk et al. 2012). Using genetic information and data on ecological differentiation for caribou and reindeer across the circumpolar species distribution range, we tested whether genetic differentiation was linked to environmental differences among populations after accounting for the confounding effects of geography. This objective was not planned initially but data from the first three objectives allowed us to link genetic and ecological differentiation in caribou/reindeer distributed under wide environmental conditions.

We first assessed neutral microsatellite genetic variation for 57 locations across the entire circumpolar native species' range, including Alaska, Canada, Greenland, Svalbard, Norway, Finland, and the Russian Federation (Figure 13). Neighbour joining tree based on genetic distance among populations split the dataset into two major genetic clusters of populations (Figure 14), which correspond to the two lineages previously described for caribou (Yannic et al. 2014), i.e., the Euro-Beringian lineage and the North American lineage. Worldwide caribou herds are also

Figure 13. Distribution of caribou and reindeer herds and ecotypes across the species' Holarctic distribution. Sampling locations are indicated by black circles. Blue: migratory tundra caribou; green: sedentary boreal forest caribou; orange: migratory mountain caribou. Spatial overlaps between ecotypes are indicated by hatching. Information on ecotype distribution was retrieved from map 2.11 of Hummel and Ray (2008) and map 28 of the Arctic Council, 2001.

broadly classified into major ecotypes, common to Eurasia and North America. Across the circumpolar distribution of the species, it is worth noting the strong genetic clustering of herds that belong to different ecotypes, even at a small scale. Sedentary herds of Alaska are for example closely related to neighbour migratory tundra herds, the exact same situation is observed among migratory tundra herds and the Torngat mountain herd of Québec and Labrador. Conversely, along the continuous range of boreal forest in Canada, a major genetic break is observed. These results suggest parallel evolution of similar ecotypes in different genetic lineages.

To simultaneously estimate the quantitative contributions of geographic distance and environment on the observed patterns of genetic differentiation,

Table 3. Results of the multiple matrix regression ("MMRR", Wang 2013) approach for quantifying the proportion of genetic differentiation explained by geographic distance (D) and environment (E). Analyses are presented for the complete dataset (Worldwide) and focusing on the main genetic lineages. Also listed is the correlation between these variables (Corr.).

Dataset	R^2	β_D	*p-value*	β_E	*p-value*	Corr.
Worldwide	0.10	0.16	<0.05	0.22	<0.05	0.39
Within North-American lineage	0.35	0.07	NS	0.43	<0.05	0.65
Within Euro-Beringian lineage	0.39	0.09	NS	0.60	<0.001	0.49

we calculated geodesic distance and environmental distance for each pair of populations. Environmental distance matrix is based on 22 environmental, ecological and topographical variables. At the circumpolar scale, we found an equal importance of environment and geographic distance on spatial genetic divergence among caribou populations (Table 3). At a regional scale, within the North-American and within the Euro-Beringian linages in America respectively, we observed significant effects of environment on genetic variation that explained more than six-fold more genetic divergence than geographic distance.

Objective 4. To study the impact of parasites (e.g. Besnoitia, liver flukes) on the ecology of caribou. To compare parasite diversity and abundance in caribou from Quebec with those from elsewhere in the Arctic.

4.1: Results on the prevalence and intensity of *Besnoitia tarandi* were detailed in our previous reports and are published in:

- Ducrocq, J., G. Beauchamp, S. Kutz, M. Simard, J. Taillon, S. D. Côté, V. Brodeur and S. Lair. 2013. Variables associated with *Besnoitia tarandi* prevalence and cyst density in barren-ground caribou (*Rangifer tarandus*) populations. Journal of Wildlife Diseases 49:29-38.
- Ducrocq, J., G. Beauchamp, S. Kutz, M. Simard, B. Elkin, B. Croft, J. Taillon, S. D. Côté, V. Brodeur, M. Campbell, D. Cooley, C. Cuyler and S. Lair. 2012. Comparison of gross visual and microscopic assessment of four anatomic sites to monitor *Besnoitia tarandi* in barren-ground caribou (*Rangifer tarandus groenlandicus*). Journal of Wildlife Diseases 48:732-738.

Results on the detection of *Mycobacterium avium* subspecies *paratuberculosis* (Map) in caribou herds are also presented in our previous report and are published in:

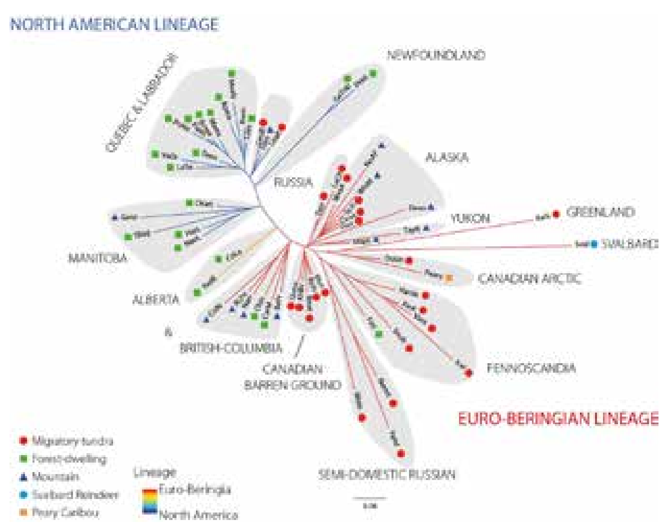

Figure 14. Neighbour-joining tree based on Nei's Da genetic distance among 59 populations of caribou analysed for microsatellites computed with the program POPULATIONS (Langella 1999). The length of the branches is proportional to the genetic distance between herds. The longest branches correspond to "island" populations (NewFoundland, Greenland, Svalbard) or smaller-size, sedentary, forest-dwelling Rangifer herds (e.g., Fenoscandinavia, Canadian boreal forest).

- Forde, T., K. Orsel, J. De Buck, D. Cooley, S. D. Côté, C. Cuyler, T. Davison, B. Elkin, A. Kelly, M. Kienzler, R. Popko, J. Taillon, A. Veitch and S. Kutz. 2012. Detection of *Mycobacterium avium* subspecies *paratuberculosis* in several herds of arctic caribou (*Rangifer tarandus* ssp.). Journal of Wildlife Diseases 48:918-924.

4.2: Comparative studies across a wide spatiotemporal range are useful for improving our understanding of health and the dynamics of wild animal populations. Indeed, population dynamics can be controlled by the overall health of individuals (Albon et al. 2002). A parasite may have an impact on the dynamics of animal populations through its effect on the life-history components of its host (May and Anderson 1978). Individual characteristics of the host may also have an impact on their rate of parasitism. Indeed, a variation in the prevalence (percentage of infected individuals in the host population) and intensity (the average number of parasites per infected host) is expected by sex and age of individuals. The size of the host population also has an impact on the prevalence and intensity of parasites, but a delay in the response of the parasite may exist, especially for environments with high seasonality.

We aimed to describe the prevalence and intensity of seven key macroparasites of migratory caribou (*Hypoderma tarandi, Cephenemyia trompe, Taenia hydatigena, Fascioloides magna, Echinococcus granulosus, Dictyocaulus eckerti* and *Taenia krabbei*) across twelve herds from Alaska to Greenland (Figure 15) and to determine which factors such as sex, age, herd size and season best explain the prevalence and intensity of these parasites after correction for the sampling year. In summary, a total of 1507 caribou/reindeer were sampled and results show a relatively uniform distribution of parasites in all herds with the exception of nose bots (*C. trompe*), liver cysts (*T. hydatigena*) and muscle cysts (*T. krabbei*), which are more prevalent in some herds. Giant liver flukes (*F. magna*) were present only in the two Québec herds, with the Rivière-George herd (95 ± 5%; n=20)

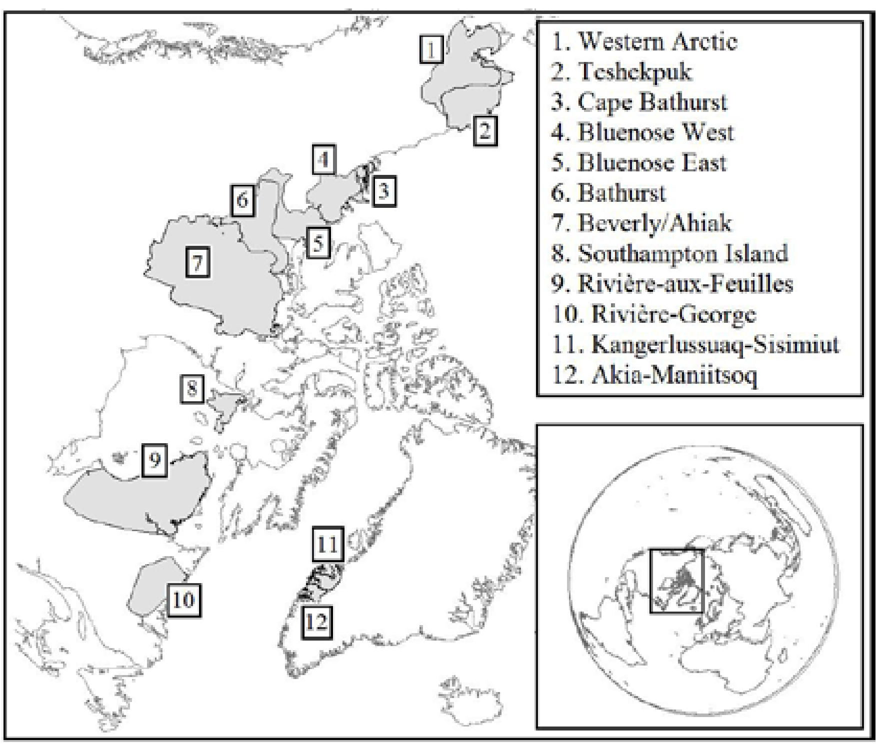

Figure 15. Annual range of the twelve studied caribou herds in North America and Greenland.

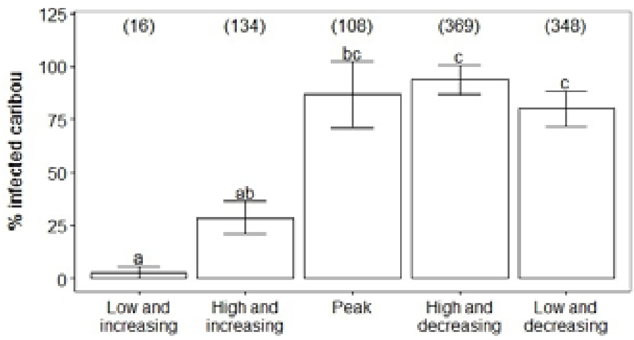

Figure 16. Prevalence (the percentage of infected individuals in the host population) of giant liver flukes (Fascioloides magna) according to herd size in caribou from the Rivière-George herd. Herd size was divided into five phases that accounted for both population size and trend: low and increasing, high and increasing, around the peak, high and decreasing, and low and decreasing. Different letters denote different means. Error bars represent mean ± SE. Sample sizes are shown in parentheses.

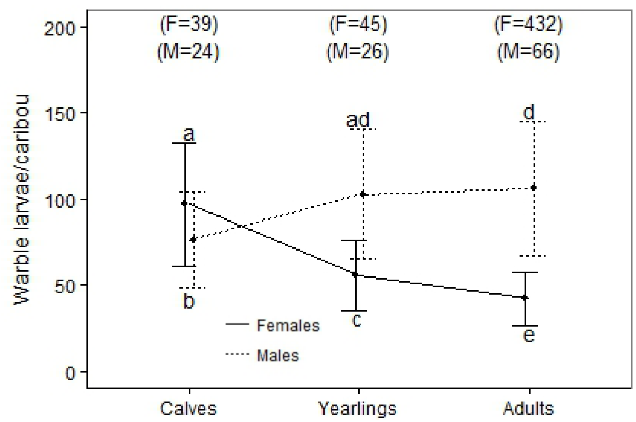

Figure 17. Intensity (the average number of parasites per infected host) of warble larvae (Hypoderma tarandi) according to age class in male and female migratory caribou. Different letters denote different means within sex and age classes. Error bars represent mean ± SE. Sample sizes are shown in parentheses.

having a higher prevalence than the Rivière-aux-Feuilles herd (40 ± 10%; n=25) (z=3.03; p=0.002). The prevalence of giant liver flukes was also higher during the population size peak and afterwards than at other times (Figure 16). The age of the host seemed to have an impact on the prevalence of the studied parasites, with adults being usually more infected than calves. For giant liver flukes, calves had a lower prevalence (19±9%; n=85) than yearlings (70±20%; n=19) (z=-3.16, p=0.005) and adults (83±7%; n=438) (z=-6.56, p<0.001). For nose bots, adults had a higher prevalence (10±10%, CI 95%; n=300) than calves (2±2%, CI 95%; n=24) (z=-2.74, p=0.02). For liver cysts, adults had a higher prevalence (18±9%, CI 95%; n=805) than calves (5 ± 4%, CI 95%; n=132) (z=-2.90, p=0.01). The intensity of warbles increased with age in males, but the opposite occurred in females (Figure 17). Finally, for most parasites, there was no significant difference in terms of prevalence and intensity between sexes, age classes, and herd size (all p's >0.05).

Objective 5. To understand the relationships between the grazing ecology of caribou and short and long term effects of climate change on the summer range of caribou.

5.1: Forage quality and quantity in early summer are especially important for the reconstitution of body mass and growth of caribou (Gunn and Skogland 1997). The match between the availability of forage and peak nutritious demands for caribou could be jeopardized by climate warming, and could decrease the recruitment of calves (Post and Forchhammer 2008). In the last two decades, Nunavik and Nunatsiavut experienced rapid climate warming. One of the most evident impact is the densification of the shrub layer (Myers-Smith et al. 2011), which could increase the abundance of forage for caribou. We aimed at evaluating the influence of climate warming and caribou browsing on the phenology and biomass of caribou food resources using a simulated experiment. Since 2009, we mimic direct and indirect temperature increases with open-top chambers and nitrogen fertilization respectively, while also simulating variable browsing pressure by caribou on American dwarf birch (*Betula glandulosa*).

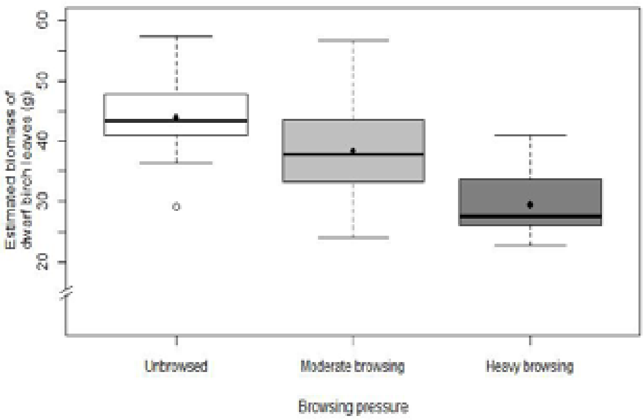

Figure 18. Distribution of estimated biomass of American dwarf birch leaves (g of dry matter) from three different browsing pressure simulated in the arctic tundra at Deception Bay, Nunavik. Both moderate and heavy browsing reduced the biomass of dwarf birch leaves. Bottom and top of the boxes denote the 25th and 75th percentiles, respectively, and the bold line within the box is the median. The whiskers show the range of the distribution. The dot in the box is the mean of the distribution, and the open circle is an outlier.

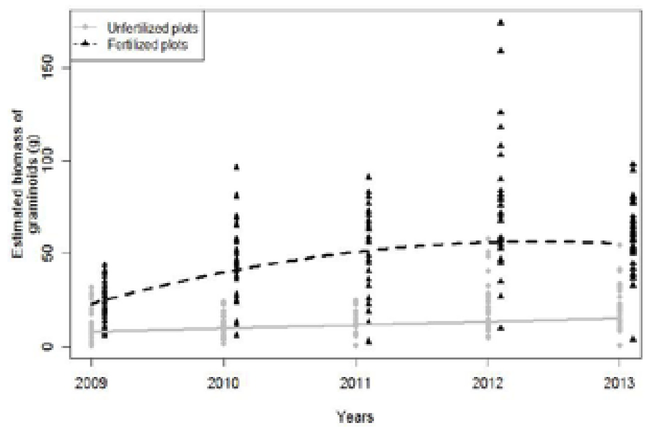

Figure 19. Changes in the biomass of graminoids (g of dry matter) under two levels of fertilization through five years of experimental treatment in the arctic tundra at Deception Bay, Nunavik. Biomass of graminoids increased with time in fertilized and unfertilized plots, although at a much lower rate in the later one. Triangles and circles represent raw data of each fertilized or unfertilized plot, respectively.

The biomass of leaves was mainly driven by the browsing treatment. After five years of moderate browsing, the biomass of American dwarf birch leaves declined by 14% (Figure 18) and did not sustain the compensatory response reported after two years by Champagne et al. (2012). Heavy browsing, typical of conditions encountered at very high caribou population levels, reduced the biomass of birch leaves by 34%. Opposite to our predictions, increasing temperature reduced the biomass of dwarf birch leaves by 13%. This counterintuitive result could be attributed to an indirect effect of the warming treatment, which could have increased evapotranspiration, thus reducing soil moisture (Marion et al. 1997) and the growth of dwarf birch (Dunne et al. 2003). The fertilization treatment did not increase the biomass of dwarf birch but strongly increased the biomass of graminoids (Figure 19), which are known to benefit from fertilization (Aerts et al. 2006). Graminoids are commonly used as forage for caribou but their protein content is lower than in birch leaves in early summer, when caribou have their peak nutritious demands (Klein 1990).

We observed an advance by four to seven days in vegetative phenological stages under an increased temperature regime (Figure 20) in 2011 and 2013, which had a late spring and low number of thawing degree-days (759 and 566 degree-days respectively) than 2010 and 2012 (801 and 815 degree-days respectively). While the advance for both years is lower than the advance of 10 days reported by Post et al. (2008) in Greenland, it contributes to reduce the inter-annual variability in the phenology of American dwarf birch.

5.2 – 5.3: Our major results concerning the tolerance of dwarf birch to variable browsing pressures through the simulation experiment described in 5.1 and on the change (or absence of change) in the horizontal cover of erect shrubs during the 1970-2010 period despite climate warming were presented in our report last year. Most of those results are now published in:

- Champagne, E., J.-P. Tremblay and S. D. Côté. 2012. Tolerance of an expanding subarctic shrub, Betula glandulosa, to simulated caribou browsing. Plos One 7:e51940.

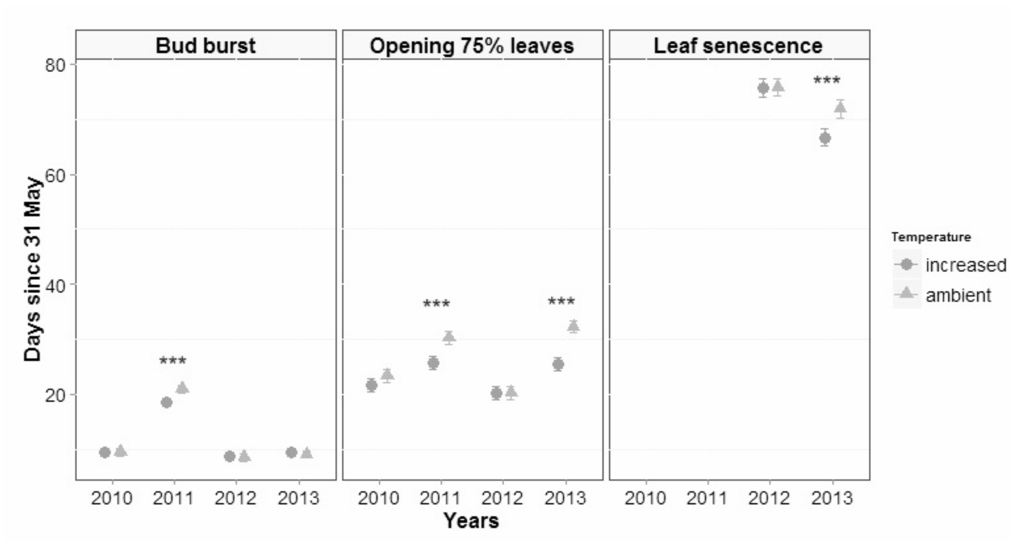

Figure 20. Estimation of the effect of warming on the phenological development of American dwarf birch in a simulation experiment conducted over five years in the arctic tundra at Deception Bay, Nunavik. Warming advanced bud burst and opening of 75% of leaves in 2011 and advanced opening of 75% of leaves and leaf senescence in 2013. Error bars represent 95% CL.

- Plante, S., E. Champagne, P. Ropars, S. Boudreau, E. Lévesque and J.-P. Tremblay. 2014. Shrub cover in northern Nunavik: can herbivores limit shrub expansion? Polar Biology 37:611-619.

<u>5.4:</u> Browsing effects on shrubs can persist multiple years after release from heavy browsing (Crête and Doucet 1998) and thus, affect resource availability for caribou over the long term. In 2011, we installed a series of 15 small exclosures (9m^2) designed to protect erect heavily browsed willows (*Salix planifolia* and *S. glauca*) from browsing. We monitor the response of willows to the exclusion of caribou since 2013. In July 2014, we removed three exclosures and we will continue to do so in the forthcoming years to identify the length of recovery at low browsing pressure required for the recovery of erect willows.

<u>5.5:</u> While the American dwarf birch was a dominant summer forage of the Rivière-George and Rivière-aux-Feuilles herds in the 1990's (Crête et al. 1990) there are reports of a much lower selection for birch (*Betula glandulosa* and *B. nana*) in northwest North America. This could be due to differences in antibrowsing defense between resin rich *B. glandulosa* in central and eastern Canada and *B. nana* in central Siberia across Beringia and in the continental tundra of North America We aim to evaluate the compositional (macroelements, hemicellulose, cellulose, fiber) attributes of *B. glandulosa/nana* over the North American range of migratory caribou and relates its chemical characteristics to soil fertility (C, N, P, pH and bulk density). As related in the report of last year, with the assistance of colleagues, we collected 150 birch leaves and underlying soil samples from 50 different locations across the North American and European Arctic. Laboratory analyses are completed and up to now we have mainly looked at the patterns of birch leaf N:P across the Arctic to characterize the spatial extent of NP co-limitation. The results strongly suggest that birch shrub growth is co-limited by N and P availability across its range (Figure 21).

Objective 6. To study the impact of predation by wolves and black bears on the population dynamics of caribou by initiating a large-scale monitoring program of predators using satellite collars.

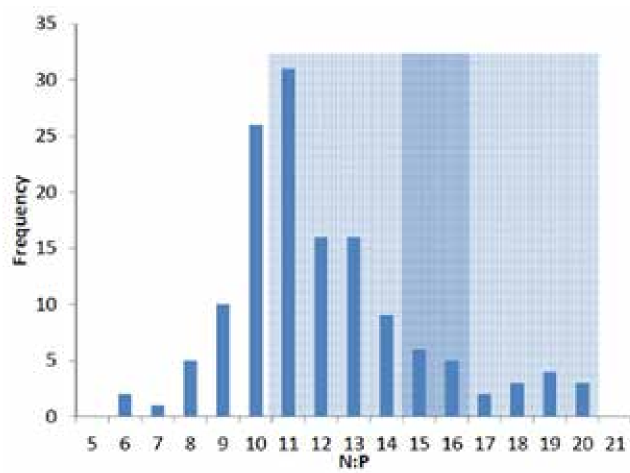

Figure 21. Frequency distribution of N:P ratio in the samples. The blue background is the range of N and P limitation suggested by either Güsewell (2004; <14 N-limited, >16 P-limited) or Koerselman and Meuleman (1996; <10 N-limited, >20 P-limited).

Wolves are considered the main predator of migratory caribou (Bergerud et al. 2008), but their impact on the population dynamics of migratory caribou is not well understood. The migration of caribou to calving grounds at high latitudes is thought to be partly a response to wolf predation. The ecology of black bears may also be greatly influenced by migratory caribou, especially on and near calving grounds where bear predation is thought to be a major source of mortality. The ecology of black bears in areas with access to caribou and in areas far from calving grounds may be very different. To investigate these questions, we began in 2011 a satellite-monitoring program of both predator species. Twenty-six black bears and 26 wolves in total on both caribou herd ranges have been equipped with satellite collars. Preliminary results revealed that individual wolves from the Rivière-aux-Feuilles herd range perform large seasonal movements comparable to that of the caribou migration (Figure 22). This observation is surprising because wolves in northern

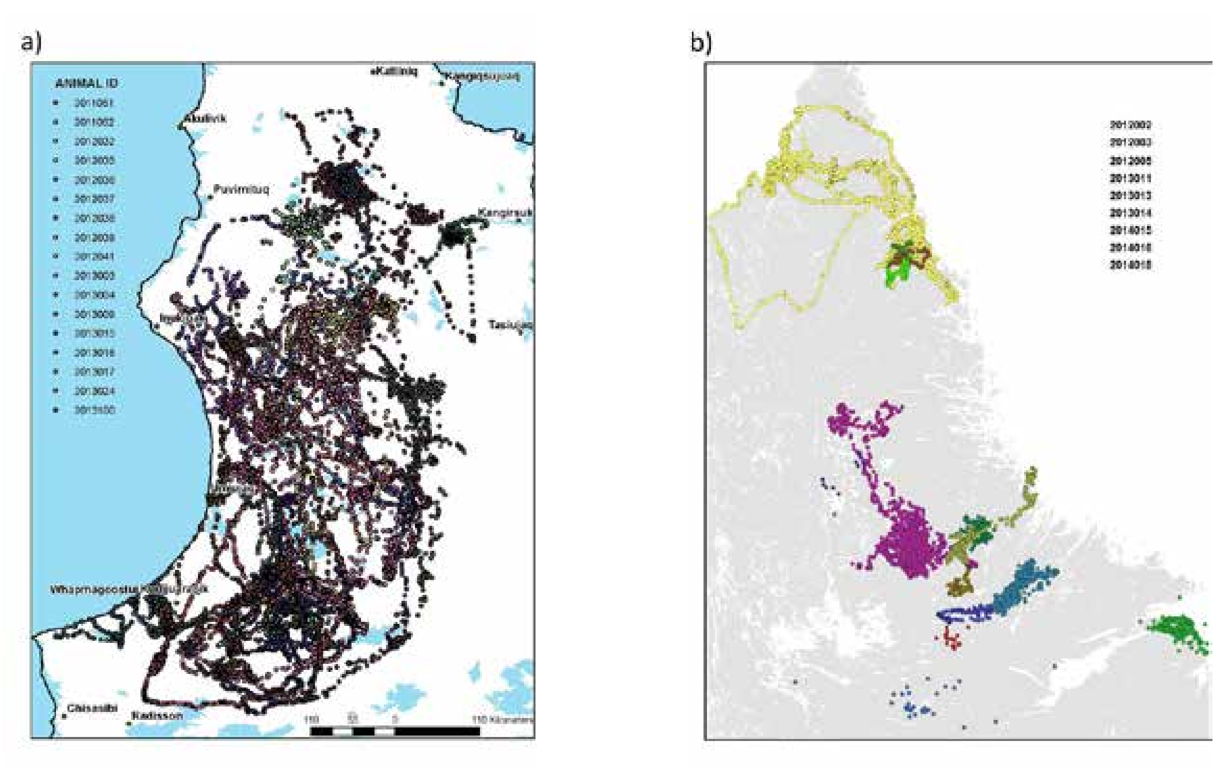

Figure 22. Locations of satellite-tagged wolves within a) the Rivière-aux-Feuilles and b) Rivière-George caribou herd range between June 2011 and December 2015.

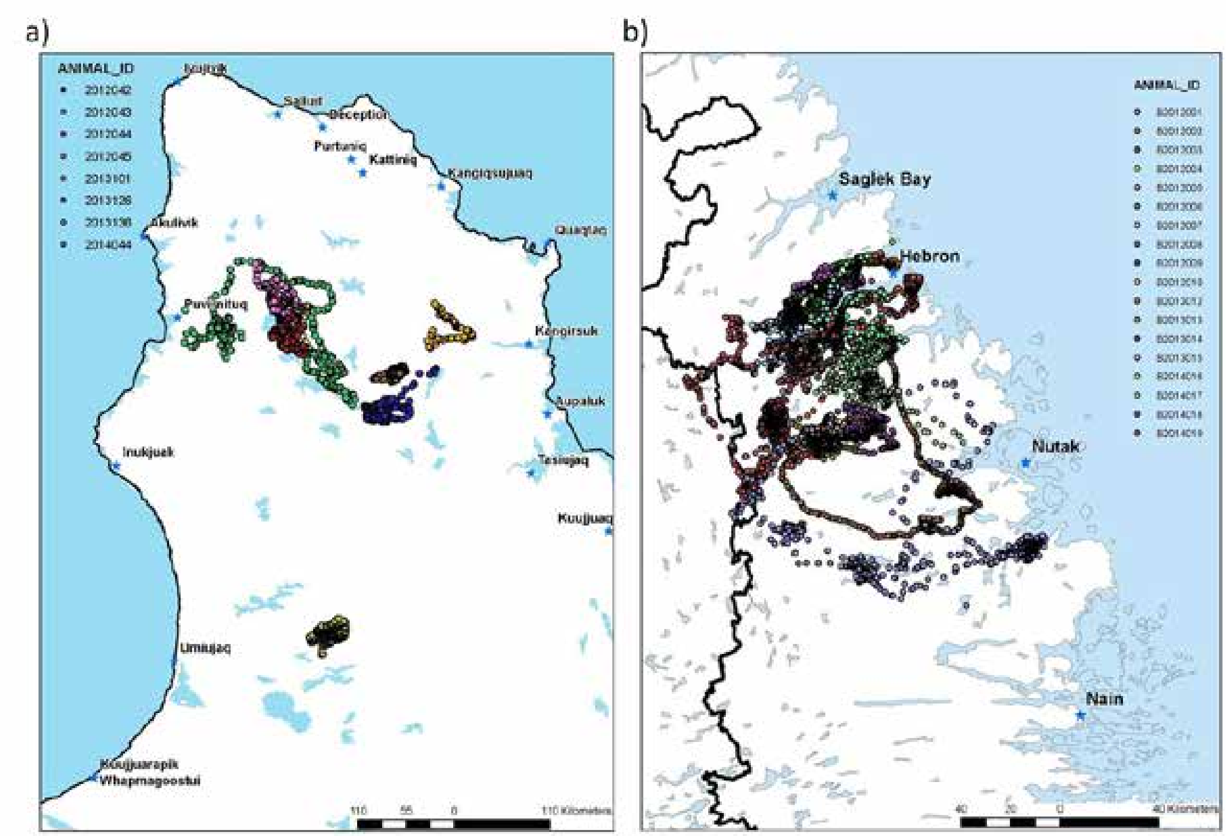

Figure 23. Locations of satellite-tagged black bears within a) the Rivière-aux-Feuilles and b) Rivière-George caribou herd ranges between June 2013 and December 2014.

Quebec were expected to be non-migratory. Our last field work sessions in June 2014 and October 2014 revealed that the abundance of wolves on the Rivière-George herd, that has decreased 98% in the last two decades, was now very low. Black bears on the Rivière-George range appear to congregate on calving grounds and locations indicate an attraction towards high-density caribou concentrations. The variation in space use of black bears is very high, with some sedentary individuals and others undertaking long movements (Figure 23). We will continue to collar predators alongside our fieldwork on caribou. The recruitment of two graduate students on this project is planned for the fall of 2015 because we have just obtained funding for the large costs of captures and the satellite program.

DISCUSSION

Objective 1. To determine life-history variation in known-age individuals, more specifically to assess longitudinally age-specific survival and reproduction of radio-collared animals.

1.1 - 1.2 -1.3: PhD 1 and MSc 1 projects are completed since 2012. The discussion on the effects of maternal characteristics on juvenile mass, size and fat storage on conception probability and on the effects of population size on maternal phenotype and fat reserves are presented in the previous reports and the papers cited in the results section.

1.4: Results on the survival rate of caribou of both herds have been discussed in the last reports. New analyses on large-scale environmental drivers of survival and recruitment variation will continue in the next phase of our research. The part of our study related to the effect of collars on caribou survival rate demonstrated potentially large negative impacts of heavy collars on survival in migratory caribou. The average difference in point estimates of annual survival between individuals equipped with light VHF collars and those with heavy satellite collars was 17.7% over 5 years. Although body condition measurements were not taken on captured individuals during this period, the herd was declining because of, in part, poor body condition in the late 1980s and early 1990s (Crête and Huot 1993, Couturier et al. 2009a, Couturier et al. 2009b, Couturier et al. 2010). Furthermore, the herd range had increased considerably during this period, resulting in annual migrations of over 1,000 km, likely decreasing body condition (Couturier et al. 2009a, Couturier et al. 2010). This suggests that during a population decline, when demographic parameters such as survival and reproduction are already diminished, the added weight of a collar, even within the suggested <3% of total body mass (Kenward 2001), may have negative implications. Although the satellite collars only weighed approximately 1.6% of the body mass of an adult female caribou (80–100 kg; Couturier et al. 2009a), compared to approximately 0.5% for the VHF collars, this difference was apparently enough to decrease survival during a population decline. In addition to the detrimental effect of weight, the size or shape of the collar may contribute to the cumulative effect of wearing a heavier radio collar. Our results suggest that the interaction between collar weight and individual body condition should also be considered. Heavy satellite collars have not been used on migratory caribou for the last decade, and survival estimates prior to that are corrected for the effects of the collar.

1.5: The discussion concerning the protection of caribou calving grounds is presented in the previous reports and the paper cited in the results section.

Objective 2. To analyze habitat selection by migratory caribou at different scales in all seasons, in particular in relation to migration routes and anthropogenic disturbance. To continue modeling the effects of climate change on the distribution of caribou. To use remote sensing tools to link changes in vegetation phenology and movements of caribou. To evaluate the extent to which inter-annual variation in the range use of migratory caribou can be explained by demographic trends and spatiotemporal changes in forage availability.

2.1: The discussion of the results concerning the method to assess the timing of migrations was presented in the report from last year and in the article cited in the results section.

2.2: During the study period caribou from the Rivière-aux-Feuilles and Rivière-George herds have shown variations in their migration patterns. Our approach, using random forest analyses, refined and completed the results presented in the last report. The effect of the demography of both herds on fall migration patterns of the Rivière-aux-Feuilles herd seem to reflect a competition for the southern winter range between herds but also between individuals from the Rivière-aux-Feuilles herd. Indeed, the presence of the Rivière-George herd at high population size appeared to constrain the Rivière-aux-Feuilles herd to the northern winter range. However, population size of both herds was not identified among the variables that affect the most the fall migration patterns of the Rivière-George herd, probably because the main migration pattern for the Rivière-George herd was toward the Labrador winter range where no overlap between the two herds occurs. Climate seems to affect patterns of migration through its impact on the movement capacity of caribou. Deep, soft snow increases the energetic costs of movements for ungulates (Fancy and White 1987, Lundmark and Ball 2008). Increased cost of migration, due to abundant snow on the ground or precipitation during migration, may have limited the ability of caribou from the Rivière-aux-Feuilles herd to shift to the northern winter range early in winter and the ability of caribou from the Rivière-George herd to migrate toward the furthest winter ranges. Temperature might also affect the migration of the Rivière-George herd through a delay in river freeze-up (Magnuson et al. 2000). Indeed migration towards the north-western winter range involves crossing mainly northern rivers that could act as physical barriers to caribou movement (Poole et al. 2010).

2.3: One of the most visible impacts of climate change is its effect on the timing of natural processes. The tendency for caribou migrations to occur earlier observed throughout the 12-year study period is consistent with most observations of other long-distance migrants (Tøttrup et al. 2006, Gordo 2007). Differences in departure and arrival dates between the two herds were likely related to differences in the length of their migrations, caribou from the Rivière-aux-Feuilles herd migrating over a distance twice as long as those of the Rivière-George herd (Taillon et al. 2015). Resource availability on winter and summer ranges influenced the departure dates of caribou for the spring and fall migrations. If individuals need to acquire a specific amount of energetic reserves before starting their migration a decrease in food availability can delay departure (Gordo et al. 2005). This is consistent with the delay observed at fall when NDVI was low in October and with the delay observed in the spring and fall when population size was high, as high population level could lead to increased competition for food (Bonenfant et al. 2009). Resource availability also appeared to influence the arrival date of the spring migration as we observed early arrival in years when snow water equivalent was low on calving grounds. The onset of vegetation growth is linked to snowmelt (Høye et al. 2007), and a lower snow abundance could provide an earlier access to resources. The timing of the migrations also depended on the climate conditions encountered by caribou during the migration. Arrival dates in the spring were delayed in years of mild temperatures and abundant precipitations during migration. Migrating through abundant melting snow, due to early spring, could increase energy expenditures (Fancy and White 1987) and possibly slow down the migration. Advanced departures in mild winters could indicate that caribou may use winter temperature as a cue to limit the impact of bad snow conditions during migration. During fall we observed early arrival when caribou encountered abundant snow. Thus, caribou seemed to migrate faster to limit the costs of moving through deep snow (Fancy and White 1987). We also observed early arrival for mild temperatures during migration. As mild temperatures could delay ice formation (Magnuson et al. 2000), caribou may attempt to migrate before freeze-up in order to limit the risk of injuries and drowning when crossing partially frozen rivers or lakes (Miller and Gunn 1986). According to our results, we expect a limited impact of climate change during the fall, because caribou showed variability in the use of their winter ranges (Schaefer et al. 2000, Couturier et al. 2009b) and thus, seem to be able to adjust their migration according to weather conditions. In spring, despite a tendency for individuals to leave winter ranges increasingly earlier, early spring conditions appeared to slow down migration and arrival date on the calving ground did not change. Thus the capacity of caribou to maintain synchrony with the vegetation onset could be limited by weather conditions encountered during migration. This synchrony is crucial for the survival of newborn calves (Post and Forchhammer 2008) and a mismatch between the date of arrival on calving grounds and vegetation green-up could be the most proximate negative impact of climate change for migratory caribou.

2.4: We have demonstrated that the Rivière-George herd shifted its core calving area on the Labrador Peninsula from a relatively large, low-lying and productive western area to a relatively small, mountainous and unproductive eastern area over the past two decades (Taillon et al. 2012). This shift occurred rapidly, with an abrupt change in the dominant space use strategies of our collared females being apparent around the year 2000. The reasons for this change are still not perfectly understood, but our work has revealed that caribou-induced changes in green forage abundance are likely partly responsible. Earlier studies, such as those by Messier et al. (1988)

and Manseau et al. (1996), provided evidence of local and landscape-scale habitat deterioration during the period of peak of the Rivière-George herd population size, but our study is the first to use remote sensing to examine changes in the abundance of green vegetation at the range-scale. Théau and Duguay (2004) examined changes in lichen abundance on the Rivière-George herd summer range and were able to identify habitat deterioration, but lichen is considered less important than green forage for parturient and lactating females during the calving period and for caribou on their summer range (Crête and Huot 1993).

Our model residual approach was somewhat successful in isolating the influence of caribou foraging and trampling pressure on primary productivity, but efforts to improve the NDVI-climate model for the two different core areas may yield better results. The negative relationship between model residuals and lagged caribou density, observed for the 1991-2000 core area, indicates that the model overpredicts cNDVI at high caribou density, thus suggesting a negative influence of caribou density on calving ground productivity. We also observed an increase in model residuals post-2001 for the 1991-2000 core area, suggesting that some vegetation recovery occurred after the area was relieved of its calving period caribou presence. This provides evidence that green forage abundance on the calving grounds is negatively correlated with calving period foraging and trampling pressure. Rickbeil et al. (2014) employed a similar model residual approach to assess the influence of caribou density on summer range productivity for four caribou herds in the Northwest Territories, and they too were able to identify negative relationships. The fact that such a relationship is not evident for the 2001-2011 core area is perplexing, however, and may suggest that other factors are important in explaining inter-annual variability in cNDVI. One plausible explanation is that the 1991-2000 core area is subject to intensive use by caribou throughout the summer, in addition to during the calving period, unlike the 2001-2011 core area, which is likely only used during the calving period; the negative relationship observed for the 1991-2000 core area may therefore be due as much to summer period foraging as calving period foraging. Estimates of summer caribou density will be incorporated in future models. Additionally, the 1991-2000 core area was probably subject to caribou use during the summer and calving periods pre-1991, but the lack of caribou density estimates pre-1991 precludes any analysis of lagged effects on vegetation productivity from this time.

Our results provide some insight into the probable causes of the observed eastward shift in the Rivière-George herd calving grounds. Migratory and nomadic ungulate populations are known to make trade-offs in large-scale habitat selection, including the trade-off between favouring forage abundance and limiting predation risk, with predation risk generally being higher in more productive, low-lying areas (Hebblewhite and Merrill 2009, Apps et al. 2013). Given this, we can consider caribou calving ground selection as an exercise in prioritization, with caribou selecting more productive areas during lean periods of high population size and selecting less productive, but potentially safer areas, during periods of low population size when forage abundance is less limiting. This appears to be the case over our two decade study period for the Rivière-George herd. During the 1991-2000 period of large and declining population size, we see the herd ranging over a large area of relatively productive terrain during the calving period. Females exhibited poor, but improving, spring body condition over the course of this period, suggesting that summer and calving period forage abundance was a factor limiting their growth and pregnancy rate, contributing to the population decline (Couturier et al. 2009a). Indeed, we found evidence of a negative relationship between cNDVI-climate residuals and lagged caribou density during this period; green forage abundance on the calving grounds was generally less than that predicted by the climate model in years with high calving period caribou density (1-year lag). However, with the rapid decline in population size during the 1990s, forage likely became less limiting throughout the annual range of the herd, allowing for an improvement in female body condition and a return to traditional calving areas that afford greater predation avoidance potential. Future work in Caribou Ungava will better investigate the role of predation in influencing Rivière-George herd population dynamics and space use (objective 6).

Objective 3. To determine the influence of past and future climate change on genetic diversity in caribou/reindeer populations throughout their circumpolar distribution. To assess the conservation units of caribou in Québec and Labrador. To test the ability of habitat selection to predict genetic relatedness among caribou.

3.1: The discussion of the results of our work on caribou response to past and future climate change across its entire Holarctic distribution is presented in details in the previous reports and the paper cited in the results section.

3.2: The discussion concerning our framework based on genetic information and ecological criteria to define conservation units in caribou from Québec and Labrador is presented in details in the last report.

3.3: The discussion on our study concerning temporal variation in landscape use and genetic connectivity of caribou was presented in details in our last report and the paper cited in the results section.

3.4: We found discrepancies between genetic and ecotype designation, suggesting convergence of morphological, life-history and behavioral traits across the species distribution range. Our results provide also strong evidence that both geographic distance and environment contributed to the evolution of spatial genetic divergence in the landscape adaptive radiation of caribou. This is a remarkable result given that most studies have found that environmental divergence explains less variation than geographic divergence (see Figure 3 in Wang et al. 2013). Yet, we used divergence at neutral molecular markers, which remains a surrogate to estimate ecologically-driven selection. Populations in similar environments should then have less divergence in genes under selection than in neutral genes.

We found a similar pattern, i.e. a more important influence of environment than geography across different spatial scales, regions and landscapes. This indicates that our results are intrinsic to our study organism, and not the result of a particular landscape. Studies of single system on single landscape are undoubtedly valuable for landscape genetics (Short Bull et al. 2011). However, comparative studies of multiple landscapes, as we performed here, provide a better understanding of organism–landscape interactions (Short Bull et al. 2011, Wang and Bradburd 2014). Patterns observed in different landscapes across the caribou range are consistent with ecologically mediated divergence, suggesting that environment plays a key role in the evolution of spatial divergence in this species. Overall, this study suggests that local environmental conditions shape patterns of spatial genetic divergence even in species with high potential for gene flow. Despite genetic differentiation across a vast circumpolar range, caribou herds have then evolved parallel morphological, life-history and behavioural adaptations within each phylogeographic lineage in response to specific ecological constraints. This could be seen as the result of local adaption.

Objective 4. To study the impact of parasites (e.g. Besnoitia, liver flukes) on the ecology of caribou. To compare parasite diversity and abundance in caribou from Quebec with those from elsewhere in the Arctic.

4.1: The first part of this objective has been discussed in details in our last report and in the 3 papers published cited in the results section.

4.2: Understanding the health and dynamics of wildlife populations can be enhanced by comparative studies across time and across populations and geographic regions. Our comparative approach to investigating parasite diversity and abundance across caribou herds provides first, baseline information on parasite diversity and abundance across herds, and second, novel insight into contemporary and historical factors influencing parasite distribution and transmission dynamics. Our results on abundance and diversity of parasite fauna in 12 caribou herds suggest that for most parasites, their distribution is relatively uniform among all herds and that there is no significant difference in terms of prevalence and intensity between sexes, seasons, and herd size, but that adults show a higher prevalence than calves for some parasites. This is an indication that macro parasites are not central in the dynamics of caribou herds because they do not covary with body condition or population density. Nonetheless, we showed that giant liver flukes were present only in the two Québec herds, with the Rivière-George herd having a higher prevalence than the Rivière-aux-Feuilles herd. We also found that the prevalence of giant liver flukes in the Rivière-George herd was higher during the population size peak and afterwards than at other times, suggesting the importance of population size in the transmission of these parasites or higher susceptibility to infection when body condition is reduced at high population size. Our research will provide the first comparative survey of *Rangifer* health across a broad geographic range.

Objective 5. To understand the relationships between the grazing ecology of caribou and short and long term effects of climate change on the summer range of caribou.

5.1: As predicted, our results suggest that browsing is the dominant factor affecting dwarf birch abundance, independently of warming and fertilization. Furthermore, heavy browsing pressure in interaction with long-term effects of climate warming decreased the fiber content of dwarf birch leaves, supporting the idea that browsing and climate warming could interact and improve the nutritional quality of dwarf birch leaves. As predicted, simulated warming advanced the phenological development of dwarf birch but only in years when bud burst or opening of leaves were late, thus reducing inter-annual variability instead of increasing it. Overall, our experiment provides robust evidence of interactions between heavy browsing by caribou and climate warming on the availability of dwarf birch.

Heavy browsing pressure was the strongest driver of birch production in our study. Browsing pressure at the landscape scale is dependent upon the size and spatial distribution of caribou herds. Population dynamics and space use of caribou are highly variable in time (Vors and Boyce 2009, Taillon et al. 2012), thus providing birch with windows of opportunity to recuperate from browsing. Interestingly, the situation may be different with semi-domesticated reindeer where populations are often maintained at high density and where dwarf birches are less defended, because of their lack of toxic secondary compounds (Bryant et al. 2014) leading to persistent impact on shrub growth (Ravolainen et al. 2011). Warming and fertilization had lower effect sizes than browsing in our study but since climate warming is directional, it can gradually affect shrub growth. Changes in the composition of plant communities in the long term could thus have stronger effects on the nutritional ecology of caribou. Graminoids are known to benefit from fertilization (Aerts et al. 2006) and responded accordingly in our study area. Nevertheless, this could be a short-term transitional effect if shrubs eventually overgrow the graminoids. If a shift in dominance from dwarf shrub to graminoids does occur under the stressful conditions found within our study area, this would likely change the nutritional value of forage available to caribou (Klein et al. 2007).

It also seems that, up to a certain limit, warming could contribute to synchronize yearly variation in phenological development of plants by advancing stages important for caribou such as leaf opening. (Post et al. 2008) have shown that asynchrony between peak in resource availability and caribou reproduction reduces the recruitment of calves in fall. The phenological stage at the opening of 75% of leaves corresponds with the moment of peak consumption by caribou (Bergerud et al. 2008),which is consistent with the observation that leaves are then high in protein and low in fiber (Klein 1990). In caribou populations that perform large migrations, the peak in energy demands to feed the calves usually occurs before the peak in forage availability. Females then rely on endogenous reserves to grow the calf (Taillon et al. 2013) and to ensure that the growth period is long enough to allow the calf to survive the fall migration. We still need to determine the effects of the reduction of inter-annual variability in dwarf birch phenology and potential synchronization with calving in those years on recruitment of caribou calves in our system using data on calf recruitment and NDVI to infer forage phenology.

Our study confirms the strong top-down effect of herbivory in interactions with edaphic and climatic factors on caribou forage. We still need to investigate how other factors related to climate change such as increased snow accumulation and shading by shrubs influence the chemical ecology of the dominant forage species and forage quantity and quality for caribou.

5.2 – 5.3: The discussion of these results was presented in the previous reports and the papers cited in the results section.

5.4: Studies conducted at the peak of the Rivière-George caribou herd in the late 1980's suggested that damage to the habitat from heavy browsing is a factor influencing the initial phase of population decline in caribou (Messier 1991, Crête and Huot 1993). We also know that the suppression of erect shrubs can persist over many years (Crête and Doucet 1998). The planned unfencing experiment on willows will allow us to understand the recovery dynamics of preferred erect shrub species. Erect shrubs such as willows are key components of the tundra ecosystem contributing to the structure of the habitat and providing cover and food for many animal species. This experiment will continue through four years as we will unfence three exclosures per annum to expose willows to browsing at different stages in their recovery. This will allow us to identify thresholds in the resilience of willows; a species that seems to be highly reactive to heavy browsing pressure.

5.5: Nitrogen is widely cited as the principal growth limiting nutrient for plants in moist, mesic and dry arctic tundra ecosystems (Nadelhoffer et al. 1992). As such, the widespread increases in deciduous shrubs that have been observed across the Arctic as the climate warmed over the past 30 years (Naito and Cairns 2011), are generally attributed to enhanced nitrogen supply due to temperature-induced increases in soil organic matter decomposition (Myers-Smith et al. 2011). Our conclusion of N:P co-limitation is important because the controls on P availability in soils are as much abiotic (e.g. pH) as biotic (e.g. decomposition; Frossard et al. 2000), implying that the impacts of climate warming on P supply to plants may be quite different to those of N supply. We will now relate the compositional (N, P) and nutritional (fibers fraction; a proxy of digestibility) of *B. glandulosa*/nana leaves to longitude, vegetation type (Walker et al. 2005) and documented use by caribou.

Objective 6. To study the impact of predation by wolves and black bears on the population dynamics of caribou by initiating a large-scale monitoring program of predators using satellite collars.

Our satellite monitoring program revealed that wolves were migratory, just like caribou, with most packs tracking the movements of caribou, at least from late summer to the spring. During the reproductive season of wolves, individuals within packs made long lone excursions in the tundra, presumably to find food to feed the pups. Members of the pack re-united at least once every 7 to 10 days. We are continuing our program on wolves with new captures planned for March and June 2015. In addition to space use and migration, we will address wolf-caribou and black bear-caribou interactions spatially. Frequent locations will allow the identification of kill sites of wolves to calculate predation rates (Webb et al. 2008). Because we will have spatial data on both predators and caribou, we will produce maps of predation risk and relate them to the spatial behavior and habitat use of caribou (Metz et al. 2012). We will also determine the contribution of caribou to the diets of wolves and black bears using analyses of feces, stomach contents, sTable isotopes, and DNA barcoding. We plan to compare life-history traits of predators that have access to caribou or not. Ultimately, our data will allow us to determine the impact of predation on the population dynamics of both caribou herds.

CONCLUSION

Recent declines in the number of migratory caribou in Northern Quebec and Labrador have negative social and economic implications, particularly for northern arctic and subarctic native cultures that rely on caribou for subsistence as well as for the outfitting industry. Changes in the distribution of caribou, as well as decreases in their abundance, are expected to continue in the near future. We anticipate that the negative effects of changes in the distribution of animals and reduced abundance of caribou will be higher than the anticipated positive effects of an earlier and longer period of vegetation growth occurring with climate change. Our data indicate that caribou abundance and distribution will change in the near future and it has already started. Our recent work on the large variation in the size and distribution of calving grounds of both herds (Taillon et al. 2012), and on the large changes in migration routes as well as winter ranges are good examples of changes to come. Managers, stakeholders and communities should be prepared for a lower abundance of animals and a less predicTable distribution, further away from communities. Future research will continue to address the factors explaining variations in the population dynamics of caribou, including consequences for survival and reproduction, impacts of climate, predators and gene flow between herds, as well as the response of caribou habitat to different climate change scenarios. Management efforts focusing on preserving high quality habitat, limiting anthropogenic landscape disturbances, mitigating greenhouse gases to reduce the potential effects of climate change, and managing hunting in a sustainable manner, could alleviate stressors on migratory caribou in the Québec-Labrador peninsula.

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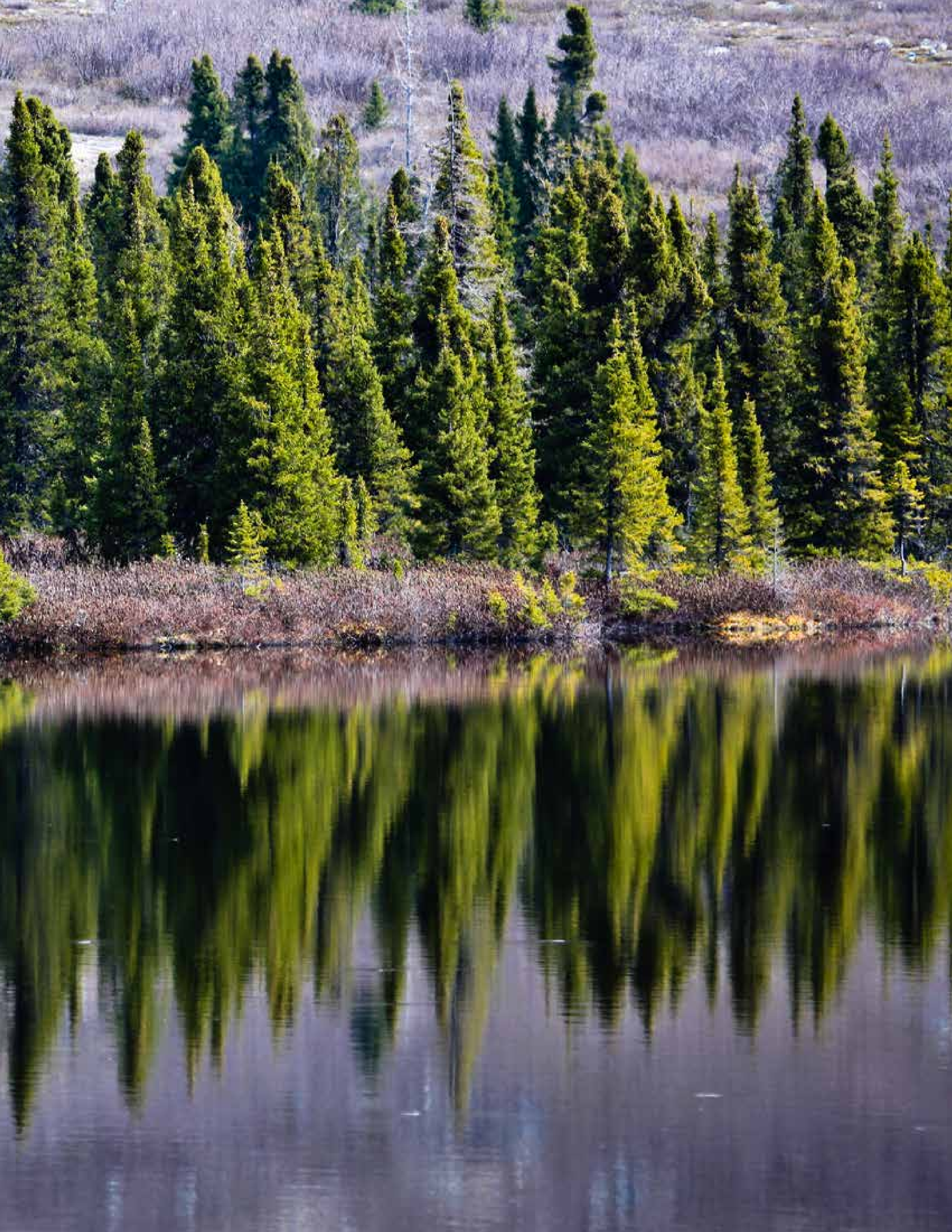

IMPACTS OF VEGETATION CHANGE IN THE CANADIAN ARCTIC: LOCAL AND REGIONAL ASSESSMENTS

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ABSTRACT

The tundra across the Canadian Arctic is already reacting to climate change. Northerners and scientists are observing changes, such as shrubs getting taller and more numerous. The taller shrubs catch more snow, and change the depth and pattern of snow drifting, which could affect travel and caribou migration. Increases in the cover of shrubs will also result in more sunlight absorbed by the leaves and this will cause more warming. The warmer climate will also affect the growth and production of berry shrub species. We study these changes near Arctic communities across the North. Community members are involved in designing the studies and in conducting measurements on tundra vegetation. An important focus of the project is the measurement of changes in amounts of berries produced each year in traditional berry picking areas near the communities. Experimental studies including warming with small open-top greenhouses and altering snow deposition with snow fences have been established to determine effects on vegetation, especially berry shrubs. We also study the insects that pollinate the berry flowers, which is crucial for berry production. These studies have been incorporated into science studies in the local high schools and used to show students how traditional ecological knowledge and scientific studies can be used together. The results will be used in the communities and will contribute to national and international efforts to understand the responses of tundra ecosystems to climate variability and change.

KEY MESSAGES

- Our research continues to engage Inuit communities across the Canadian Arctic, emphasizing research partnerships linking science and Inuit Qaujimajatuqangit (IQ) and education.
- Providing opportunities for Youth and Elders to spend time on the land together deepens their connections, and greatly enriches the appreciation of the link between scientific studies and traditional knowledge. We continued to work with communities to provide these opportunities through "land camps", "plant walks" and outdoor school activities, and to record some of the trips on video.
- Detailed Inuit observations of vegetation and climate change for eight communities will be published in thematic posters and booklets, and a book in spring 2015. Manuscripts are complete and are being translated.
- A book of berry ecology with stories and recipes in Inuinnaqtun and English for the Kitikmeot region, Nunavut, will be published in summer 2015. The book will be used in the community to help promote the use of Inuinnaqtun in schools.
- Berry production in four species is highly variable across the Canadian Arctic. Productivity has been measured in communities by community-researchers (mainly high school students) across the Canadian Arctic since 2008. We have berry and vegetation data from 22 communities and two research stations, which is the largest such network in the Arctic nations. In 2014-2015, berry productivity was measured in Umiujaq and Kuujjuaq in Nunavik, in Alexandra Fiord, Iqaluit, Pond Inlet, Bylot Island, Kugluktuk and Arviat in Nunavut, and in Saglek and Nain in Nunatsiavut. A synthesis of these data is a high priority and is underway. It will be the first study to examine spatial and temporal variability in berry production in the Canadian Arctic.
- Local scale environmental conditions affect berry productivity more than regional climate variability. Studies continued on the effects of site conditions on berry productivity, including soil, microtopography, and plant composition at Arviat and Kugluktuk (Nunavut) in 2014. These will complement studies from Nain (Nunatsiavut) and Baker Lake (Nunavut).
- Identification of pollinators and their abundance. Sam Robinson and Sylvie Ferland completed their MSc studies on pollinators at Alexandra Fiord and Baker Lake, respectively. Flies were identified as the most common pollinators and their abundance was related to weather conditions and plant phenology.
- Commercialization of *Rhodiola* (Nunatsiavut). Ecological and phytochemical analyses as well as horticultural trials and community consultations provided solid background information for a Business Opportunity Analysis, currently under review by the Nunatsiavut Government.
- Our studies have resulted in curriculum development and delivery of educational programs in Nunavik (*Avativut*) and Kugluktuk (Sarah Desrosiers, MSc research). Our community-based programs contribute to increasing the interest among Inuit students for environmental science by connecting them more closely to their territory and local ecological knowledge from their Elders and other knowledge holders. Students were clearly most interested in the hands-on and field activities and interviews with the Elders. The students that benefit the most from the activities are those less involved in the more formal ways of teaching science.

OBJECTIVES

General (overall objectives for the project)

- Determine changes in vegetation near Arctic communities using scientific studies and Inuit traditional knowledge (IQ) and establish permanent monitoring studies with communities;

- Study the ecology of the main berry species used by Inuit across the Canadian Arctic and determine their responses to experimental and observed environmental change;
- Contribute to national and international research on vegetation changes in the Arctic to better understand the effects of short-term climatic variability and long-term trends on Arctic berry plants;
- Contribute to studies of pollinating insects in the Arctic such as the NSERC CANPOLIN network;
- Generate relevant bio-climatic indicators to support vegetation studies and modelling efforts;
- Develop a network of community researchers using scientific studies and IQ to maintain a sustainable community-based environmental monitoring programs assessing climate change impacts on vegetation, particularly on berry productivity and shrub growth;
- Stimulate local student interest in Science, Math and Technology through hands-on activities in the field and contribute to local capacity-building.
- Leave a legacy of studies that will continue to be supported within the communities by local and regional organizations.

Specific objectives for 2014-2015

Nunatsiavut

- Continue studies of berry productivity in response to experimental warming and landscape position plots near Nain with community-based researchers and in Torngat Mountains National Park with Parks Canada staff. The goal is for these studies to continue with Parks Canada staff.
- Continue studies to develop the potential commercialization of *Rhodiola rosea*. Studies include:
  - » growth, and habitat of wild populations of in coastal ecosystems of Nunatsiavut to guide selection of appropriate cultivars for community garden trials to grow these valuable medicinal plants;
  - » monitoring and expanding community garden trials of *Rhodiola* in target communities in Nunatsiavut (Nain and Rigolet) as well as the botanical garden at Memorial University to help determine optimal local cultivars and growing conditions for cultivation of *Rhodiola*;
  - » phytochemical analysis in conjunction with field trials in order to determine the effects of environmental conditions on medicinal potency, growth, and reproductive biology of Rhodiola grown in Nunatsiavut; and
  - » collecting ethnobotanical data in Nunatsiavut communities (Nain, Rigolet, and Goose Bay) through focus groups and semi-structured interviews, to inform sound collaborative development of a community-based enterprise.
- Develop and submit a business plan to the Nunatsiavut Government for a community-based enterprise based on cultivation, harvesting and processing of *Rhodiola rosea*.
- Host a community open house in Nain to disseminate research results and discuss their implications for the community and region, and future directions for this research based on community needs and goals.
- Facilitate the planning of a future community-based enterprise that is culturally appropriate, ecologically sustainable and economically viable.

Nunavik

- Continue to support the environmental monitoring program *Avativut*, on vegetation and berry production, ice phenology and permafrost in the schools throughout Nunavik with the Kativik School Board.

- Develop video and web-based resources on methods for environmental monitoring for the *Avativut* program.
- Produce outreach for Nunavik students from the data they collected on berry productivity.
- Explore the perceptions and experiences of the students involved in the outdoor monitoring through the *Avativut* program and in the context of other environmental and cultural initiatives.
- Submit scientific papers on TEK-IQ interviews on environmental changes in Nunavik.

Nunavut

- Obtain feedback from Elders in Kugluktuk on the first chapters of the bilingual "Berry Book" for the region to ensure berry ecology and terminology in Inuinnaqtun are correct and to gather more stories and recipes.
- Continue training high school science students in plant identification and berry and vegetation measurements as part of their summer Career and Technology Studies week in Kugluktuk.
- Establish new monitoring plots for berry production and vegetation change with community-based researchers in Arviat, Nunavut.
- Continue observational and experimental studies of berry shrub ecology and production at the field stations at Alexandra Fiord and Daring Lake (NWT).
- Complete a study on the use of digital photography to monitor tundra vegetation and berry productivity.

Pan-Canadian Arctic studies

- Develop methodology for using camping trips (e.g. land camps, environmental summer camps, CTS courses) with Elders and Youth in communities to provide better opportunities for transmission of knowledge.
- Translate and publish the booklet " What we see! Inuit talk about environmental changes in the Arctic" and associated community posters.
- Compile environmental and traditional knowledge on berries from interviews conducted in communities from 2007-2011.
- Complete and submit a manuscript linking Inuit observations of environmental change with recent local climate records across eight communities in Arctic Canada.
- Complete data analysis and a manuscript on berry plant response to two years of experimental warming across our network of experimental warming sites.
- Complete chapters on the ethnobotany and taxonomy of *Rhodiola rosea* throughout its range in northern Canada.
- Complete a manuscript comparing ethnobotany of Nain, Nunatsiavut and Kangiqsualujjuaq, Nunavik.
- Begin compilation and analysis of berry production in relation to climate and local environmental factors from all community-based monitoring plots across Arctic Canada.
- Document the ecology of northern plants, with a focus on *Rhodiola* and shrubs, more specifically, the berry producing shrubs (distribution, growth and production factors).
- Study the interaction of vegetation structure with snow and permafrost.
- Characterize the role of microclimate (abiotic conditions) and canopy structure (biotic interactions) on the distribution and performance of three coexisting berry shrubs across the forest-tundra ecotone (Nain and Umiujaq).
- Test the effects of warming on microclimate and performance of three coexisting berry shrubs in treeline and tundra ecosystems.

Community-based monitoring

- To develop innovative and interactive material to assist teachers and students.
- To work in collaboration with the Kativik School Board and the Nunavut Department of Education curriculum developers.
- To implement the *Avativut* Ice Mission and Permafrost Observation units within the science curriculum.

Traditional and local knowledge

- To develop a field methodology where we collaborate with northern communities to organize land camps with Elders and Youth. Being on the land provides unique opportunities and contexts for the Elders to transmit their traditional knowledge and wisdom to the Youth. We believe that, by doing so, we can access a level of information that is hardly available through formal indoor interviews. The Youth will engage and relate more with their Elders in such a context, which is beneficial for the knowledge transfer and the development of a strong cultural identity. Researchers become facilitators by helping to collect, record, analyze and archive the information gathered from knowledge holders, including plant ecology and plant traditional uses.
- Document and synthesize Indigenous knowledge of change in treeline and tundra vegetation (in particular berries and *Rhodiola* but inclusive of other environmental variables related to weather, physical factors and animals) in light of local climate trends.

INTRODUCTION

Our project is focussed on impacts of climate change on vegetation near Arctic communities and the responses of the four major berry shrub species found across the Arctic. Recent syntheses of warming experiments (Elmendorf et al. 2012a) and long-term changes in tundra vegetation (Elmendorf et al. 2012b) show the that warming increases the height and growth and shrubs. These field-based studies support the increased "greenness" in the tundra region found in remote sensing studies using NDVI (Bhatt et al. 2010). These changes are also being observed by residents in the communities throughout the Canadian Arctic. Many Elders and other northerners report an increase in the cover and height of shrubs, and that there are more trees in areas in the forest-tundra (Henry et al. 2012). These changes impact travel routes of hunters and others across the landscape. The changes will also affect the forage available for important wildlife, such as caribou and muskox.

Berry picking is an important activity in all communities and they provide important nutritional benefits. We focus studies on the berry production of four species near communities, which allows incorporation of both scientific and traditional ecological knowledge – Inuit Qaujimajatuqangit (TEK-IQ) studies. Since 2008, our project has established berry monitoring plots near 22 communities, and monitoring is done by high school classes or by students in summer science/TEK-IQ camps. In some communities and at two research stations, warming experiments are established at the berry plots to determine the impact of warming on production. The goal is to have students learn how to conduct vegetation monitoring and to learn about the changes in the vegetation and in berry production from their Elders. As of fall 2013, all of the high schools in Nunavik are involved in environmental monitoring as part of their science and technology curriculum and they are using our berry monitoring protocols in this special program (*Avativut*: http://www.cen.ulaval.ca/avativut/en_accueil.aspx). Ultimately, we hope to have this type of environmental monitoring incorporated into the school curricula across the Arctic.

Berry production in these species depends on pollination by insects. However, it is not known which insects are the important pollinators for the shrubs (and other species). We also do not know what the impact of warming may be on the pollinating insects relative to the plants. We are conducting some of the first studies of the pollinators of these species in our research sites, connected to the CANPOLIN project across Canada.

Another potentially important species for communities in Nunatsiavut is the medicinal plant, *Rhodiola rosea*, which is native to northern Labrador. However, little is known about the basic ecology of *Rhodiola* populations in Labrador. The increased shading expected with the trend toward a more shrub-dominated vegetation in the Arctic (Elmendorf et al. 2012; Myers-Smith 2011), along with other effects of climate change, could affect plant species such as *Rhodiola* in unpredictable ways. The effects of climate change upon the growth and medicinal properties of *Rhodiola* have not been addressed (Cavalier 2009, Downing and Cuerrier 2011). Additionally, little is known about how Inuit perceive the use of their traditional knowledge within a commercial venture (Cuerrier and Arnason 2008, Black et al. 2008, Hindle and Lansdowne 2007). We address these unknown aspects of the biology, medicinal properties, and response to climate change of *Rhodiola* in Labrador, while also investigating the attitudes towards integrating traditional knowledge with commercial enterprises in Northern Aboriginal communities.

Incorporating both scientific and TEK-IQ approaches, we aim to better understand the changes in vegetation and berry production in response to climate variability and change across the Canadian Arctic. We also hope that the set of monitoring sites in communities monitored by students will provide the long-term data required to understand the changes; and that the studies will inspire northern students to pursue careers in science.

ACTIVITIES

Nunatsiavut

- Permanent berry productivity plots were sampled in Nain and Saglek.
- *Rhodiola* seeds will be put into germination beds in March 2015 at the Montreal Botanical Garden and plantlets will be brought back to Nunatsiavut to expand cultivation.
- *Rhodiola* specimens gathered sustainably from wild Labrador populations, propagated through root divisions and planted at two field sites (Nain and Rigolet) and MUN Botanical Garden in August 2012 (107 plants total) were monitored in Aug 2014.
- Pictures of caterpillar and butterflies were taken for identification and integration into the database of eButterfly in partnership with Dr. Maxim Larrivée (Insectarium of Montreal and co-founder of eButterfly).
- Dwarf birches were sampled in the Ivitak Valley and Nain, in partnership with Dr. M. Te Beest (Ůmea University, Sweden), for a global synthesis of tundra herbivory and its impact on vegetation change in the face of climate change.
- Dwarf birch monitoring plots established by our team in 2011, were re-surveyed in Nakvak Brook and Ivitak Valley sites in partnership with Parks Canada (Dr. Darroch Whitaker). These data are archived with Parks Canada as one of their climate change indicators for the TMNP monitoring strategy.
- Nakvak Brook OTCs were replaced and repaired as necessary (Torngat Mountains Basecamp and Research Station). Soil and air temperature data downloaded in July 2014.
- A Business Opportunity Analysis for potential community-based enterprise in Nunatsiavut was submitted to the Nunatsiavut Government (NG) in May 2014. Discussions with the NG Economic

Development Department representatives and a Memorial University Business professor are underway to determine if the NG is interested in moving forward with this potential business opportunity.

- Plant hikes from Torngat Mountains Basecamp and Research Station were led by Alain Cuerrier and Luise Hermanutz in July 2014. They both gave seminars on impacts on climate change on tundra vegetation, and ethnobotany in Nunatsiavut to a general audience at the basecamp in July 2014. The talks were part of the “Science” presentations. The audience was made up of students, tourists, NG Elders, PC staff and basecamp staff.

Nunavik

- Development of the Permafrost Learning and Evaluation Situation (LES). This project is a joint initiative of Sarah Aubé-Michaud (Université Laval), Michel Allard (U. Laval), Ghislain Samson and Esther Lévesque (UQTR). A Computer Technology teacher (CEGEP Trois-Rivières) was approached to coordinate the development of an interactive simulator to teach the basics of Permafrost dynamics and processes, this activity is directly supported by a grant from AANDC (Allard).
- Strengthening of the partnership with Kativik school board and alignment of the *Avativut* program to the school board needs. A succession of meetings were organized including: a meeting in Montreal with the curriculum developers of the Kativik School Board (KSB), Daniel Lafleur and Susan Nelson; a meeting with the General director of the KSB, Ms. Annie Popert, in Kuujjuaq (August 2014) and; a follow-up meeting with KSB representatives in Montreal (December 2014). Ms. Popert was very receptive and asked for *Avativut*’s specific needs and how KSB can contribute.
- Editing and publication of the book “Environmental changes: Inuit observations across the Canadian Arctic.” José Gérin-Lajoie translated all the text into French. After a number of meetings with Neil Christopher from Inhabit Media (Iqaluit, Nunavut), the Inuit-owned publishing company agreed to take on the publication of the book. It will be released by the end of March 2015 with the contribution of Arctic College, Université du Québec à Trois-Rivières, Université de Montréal, Memorial University, University of British Columbia and World Wildlife Fund.
- Organization of a land camp at Douglas Harbour near Kangiqsujuaq to document different ways of observing and interpreting the territory. José Gérin-Lajoie met with KRG and Makivik representatives in Kuujjuaq to discuss the feasibility of a land camp organized in collaboration with the local NV and Nunavik Parks. A community consultation was also organized in Kangiqsujuaq by Gérin-Lajoie and Hébert-Houle (March 2-6th).
- Completion of the documentary film “Nallua” shot in Pond Inlet and its surroundings.
- Ms. Popert (Director General of KSB) participated in the berry productivity monitoring activity on the land, with Sec. 1 students of Jaanimmarik School in Kuujjuaq together with MSc student Émilie Hébert-Houle and José Gérin-Lajoie.
- Preliminary fieldwork for MSc. student Isabelle Lussier in Umiujaq, Nunavik (assisted by Alexandre Bérubé Tellier, undergraduate BSc. student) with the collection of berries from 30 well documented plots covering a range of erect shrub abundance (sparse to dense cover) and structure (low to tall shrub).

Nunavut and NWT

- Berry production, vegetation, climate and soils data were collected in long-term monitoring plots and experimental warming plots at the Alexandra Fiord research site, Ellesmere Island, (Nunavut), the Bylot Island research station (Nunavut) and the Daring Lake research station (NWT).

- Berry productivity monitoring in Iqaluit continued in collaboration with J. Carpenter and students in the Environmental Technology Program at Nunavut Arctic College.
- The permanent ITEX site established in 2013 on Igloolik Island (consisting of 10 experimental warming (open-top chambers) and 10 control plots) was monitored in collaboration with the Nunavut Department of Environment and Nicolas Lecomte (Canada Research Chair in Polar and Boreal Ecology, University of Moncton).
- Field work in Arviat. Noémie Boulanger-Lapointe conducted fieldwork in the vicinity of Arviat as part of her PhD research. She surveyed 33 sites for vegetation composition, berry productivity and animal activity. The animal activity study is also part of an international effort led by the ITEX Herbivory Network to create standard monitoring protocols.
- Field work in Kugluktuk. Noémie Boulanger-Lapointe and Sarah Desrosiers revisited the permanent berry monitoring sites established since 2008 and characterized 20 new sites. As in Arviat berry productivity but also vegetation composition and animal activity were evaluated in each plot. Activities related to plants and ecosystems were held with the Culture and Heritage high school class in the vicinity of the community over three days. A four day camping trip was organized bringing students and Elders from the community out on the land.
- Strengthening of the partnership with the Nunavut Education Department. Discussions were held with Michelene Reineger in Arviat to adapt education material developed as part of the *Avativut* to the new Nunavut Science Curriculum. Noémie Boulanger-Lapointe participated to the Kivalliq Science and Culture Camp that brought high school students from across the region to Rankin Inlet. She delivered activities on edible plants and plant identification.
- Completion of the bilingual Berry Book for Kugluktuk. During visits to Kugluktuk in 2014, Sarah Desrosiers consulted community members and organizations such as the Department of Environment and the Hunters and Trappers Association as well as the Kugluktuk women's group regarding the first draft of the "berry book". The book will describe the ecology, stories and recipes in both Inuinnaqtun and English of the berry producing shrubs in the region. Emily Angulalik became co-editor of the berry book and her students enrolled in the Inuinnaqtun Language Program are currently translating content for the book. The Nunavut Department of Culture and Heritage granted $14,000 to be spent towards the translations and printing of the book.
- Samuel Robinson completed his MSc thesis on pollinator activities and the impact of pollination and experimental warming for seed production conducted at Alexandra Fiord, Ellesmere Island (Title: *Insect Pollination and Experimental Warming in the High Arctic*) (April 2014).
- Carmen Spiech completed her MSc. thesis entitled *Une caractérisation de la distribution des arbustes producteurs de petits fruits ainsi qu'une évaluation sur deux années de la productivité de Empetrum nigrum L. et Vaccinium vitis-idaea L. à Baker Lake, Nunavut* (April 2014).
- Sylvie Ferland completed her MSc. thesis entitled *Étude sur la pollinisation du bleuet autour de la communauté de Baker Lake (Nunavut)* (April 2014).

RESULTS

- **Document and synthesize Inuit knowledge of plants.** Community consultations with Inuit traditional ecological knowledge (TEK) holders in seven coastal Canadian Arctic communities were analyzed with instrumental climate records. Our results show complexities and commonalities of environmental changes observed in the communities, and many of these changes correlated with increasing precipitation over the 30-year period. Although we identified a few common observations among all communities, there was no clear pattern in participant responses, even among communities in close geographic proximity, suggesting local controls on climate variability and observed environmental change. A manuscript describing the results is in revision for *Climatic Change*.

- **Characterize the role of microclimate (abiotic conditions) and canopy structure (biotic interactions).** In July 2010, we conducted extensive vegetation surveys across the forest-tundra ecotone, surrounding the community of Nain to characterize plant community composition, structure and microclimate in relation to berry shrub distribution, growth and fruit production. We found that fruit production was highest for bilberry (*Vaccinium uliginosum*) followed by redberry (*V. vitis-idaea*) and crowberry (*Empetrum nigrum*). For all species, we observed the highest fruit production in the upper forest-tundra transition zone, followed by the low shrub tundra, lower forest-tundra transition, and forest zones. These results indicate that fruit presence and abundance is strongly linked to abiotic conditions and canopy structure across the forest-tundra ecotone.
- **Test the effects of experimental warming on plant performance**. In July/Aug 2009, we established experimental warming chambers with paired control plots in Nain and Torr Bay area of Torngat Mountains National Park. Environmental conditions, growth and fruit production have been monitored annually since, with plans to re-sample (5 years of warming data) in summer 2015. These data have been combined with similar data from three other coastal Canadian Arctic locations to produce a multi-species, multi-site analysis on the relationship between upright deciduous shrubs [primarily dwarf birch (*Betula glandulosa*) and three dwarf ericaceous berry shrubs (bilberry (*Vaccinium uliginosum*), redberry/lingonberry (*Vaccinium vitis-idaea*) and crowberry (*Empetrum nigrum*)) under experimental warming conditions. We found that hurdle models are an effective means to model change in fruit production, and that dwarf berry shrub cover is an important predictor of fruit production. Deciduous shrubs do constrain dwarf shrub fruit production, although the effect varies among species, and after 3 years, there is a warming effect on fruit production in crowberry.
- ***Rhodiola* cultivar selections and horticultural trials**. Data were collected to determine differences in growth and reproduction in *Rhodiola* among growth substrate types and locations in coastal Labrador. Measurements of *Rhodiola* growth and reproductive productivity were made across substrate types and along a latitudinal gradient between Nain to Rigolet. Results showed that rhizome biomass was much greater in southern populations, particularly in sandy and organic substrates. *Rhodiola* specimens gathered sustainably from wild Labrador populations were propagated through root divisions and planted at two field sites (Nain and Rigolet) and MUN Botanical Garden in August 2012 (107 plants total). Trial plots were monitored in Aug 2013 and 2014. In 2013, the survival of the plants in the MUN-BG and those grown in the Nain common garden was over 95%. However, the Rigolet garden was completely destroyed by an animal, probably a fox. In 2014 the survival rates of *Rhodiola* planted in the Nain trial gardens had decreased, likely as a result of poor drainage and/or excess organic matter at the site. Further trials will be necessary to fully assess appropriate conditions for cultivation of *Rhodiola* in Labrador.
- **Rhodiola phytochemical analysis**. Labrador *Rhodiola* contain key phytochemical constituents known for medicinal potency (tyrosol, salidroside, rosarin, rosavin, and rosin). Substrate (Figure 2) has a significant effect on phytochemistry as less tyrosol and salidroside in rocky substrates, less rosavin and rosarin in sandy soil.

- **Production of educational material**. *Avativut* Program has released two video clips to explain the protocols for interviewing local experts and observing ice, in Inuktitut, French and English. PermaSim, a mobile, interactive and visual tool to teach thermal regimes for Nunavik communities, was developed as part of the Permafrost LES (Fall 2014) (see Figure 3).
- **Impact of *Avativut* Program**. *Avativut* Program contributes to raise interest in Inuit students for environmental science by connecting the learning activities more closely to their territory and local environmental expertise. Students have a greater appreciation for the hands-on and field activities among all *Avativut* activities. The students that benefit the most from the *Avativut* activities are those hardly taking part in the more formal ways of teaching science. The inclusion of local knowledge holders in the *Avativut* activities significantly contributes to students' interest. The use of their native language and their presence on the land are important factors that contribute to students' sense of value in the program.
- **Identification and quantification of pollinators at Alexandra Fiord and Baker Lake**. Flies were identified as the most common pollinators at both Alexandra Fiord and Baker Lake. Pollinators abundance was related to weather conditions, such that rain and wind prevent visit by pollinator. The abundance of pollinators could also be related to plant phenology showing the synchronicity between resource availability and temporal dynamics of insects.

DISCUSSION

Our berry ecology studies continue to show the importance of local environmental factors on berry productivity (Tolvanen 1995; Krebs et al. 2009; Henry et al. 2012). We have found important variability in the productivity of the four focus species among the sites and between years (Henry et al. 2012). At the local landscape scale, studies show that local environmental factors such as soil moisture and canopy coverage have a major impact of berry productivity. Berry productivity data collected in 2014 in permanent monitoring plots adds a seventh year for some sites in a growing data set from communities and other research sites across the Canadian Arctic. The synthesis of this long term data set is planned for the fall of 2015 (part of the PhD project of N. Boulanger-Lapointe) and will be presented at the ASM 2015.

One of the important factors in berry production is the availability and success of pollinators (Usui et al., 2005), yet which insect species act as pollinators varies greatly among sites. Bumble bees, known to be good pollinators of bell-shaped flowers such as those in the four berry producing species, were abundant in the sites in Nunatsiavut but rarely observed on blueberry plants in Baker Lake and Alexandra Fiord (Nunavut). Our results indicate that smaller flies are important as pollinators, at least for blueberry (*Vaccinium uliginosum*), and that there may be a shift to greater reliance on flies with latitude. The low ratio of berries to flowers for blueberry is likely due to the lack of pollinators, and we continue to investigate this in the other species. Our data shows no mismatch between flowering phenology in blueberry and temporal dynamics of the insects; however, we still need longer-term data. Our continued research on the effects of experimental warming on the shrubs and the abundance (and diversity) of pollinating insects, shows that the OTCs appear to reduce the number of potential pollinators, but not the diversity or the temporal pattern of the insect community.

The *Avativut* Program has now been more fully integrated into the curriculum for schools administered by the Kativik School Board (KSB). The Director General of KSB fully supports the program and encouraged a closer collaboration with the Inuit teachers and curriculum developers in the future. KSB is also looking for funding specifically dedicated to this program (e.g. AANDC-New Paths for Education), which would greatly facilitate its sustainability. One of the biggest constraints we have faced to date is the teachers' lack of awareness of their participation in a real scientific project and the importance of the data students are collecting. KSB has offered the possibility for us to participate in the Orientation Week to better inform newly hired teachers about the *Avativut* Program before the start of the school year. This introduction to the program would greatly contribute to its pedagogical and scientific success. We will also propose a protocol to encourage a better collaboration between the southern Science teachers and the Inuit Culture teachers. This teamwork would facilitate some logistics of the fieldwork and interviews with Elders, and would promote a better link between the standardized science methods and the local expertise. We plan to produce a training video for teachers on the protocols so they have access to the training throughout the year. The results from Hebert-Houle's research project on student perceptions and interests in the activities within the *Avativut* program allow us to adjust the program to enhance the students' experience.

We continue to look for opportunities to encourage the development of programs like *Avativut* in the other Inuit territories. Our work with communities has been acknowledged by agencies in the territorial governments of Nunavut and Nunatsiavut. Discussions with the Nunavut Department of Education in Arviat, and the recent invitation for J. Gérin-Lajoie to speak at the Nunavut teachers conference allow the dissemination of our results from communities across the Canadian Arctic, including the *Avativut* program. We hope these opportunities will help to inspire the development of sustained community-based environmental monitoring programs that have a strong educational component linking science and local knowledge.

Our land camp approach as a research method has become more collaborative by building the project with the community from the start. A consultation process will take place in Kangiqsujuaq in March to meet with community members and discuss the feasibility of a jointly organized land camp. Work done in Kugluktuk over the last four years has shown the importance of building relationships with schools and community members. The land camp in 2014 in Kugluktuk was organized by the high school who trusted the work done for a number of years by Sarah Desrosiers (MSc student) in the community.

Research completed on the medicinal properties and ecological descriptions of *Rhodiola rosea* in Nunatsiavut led to a formal proposal for commercialization to the Nunatsiavut Government. This project shows how scientific and traditional knowledge can work alongside public consultations to bring new economic opportunities to northern communities.

CONCLUSION

Over the years, we have collected a unique data set on berry plant ecology across the Canadian Arctic. We are only now starting to understand the impact of environmental and climatic factors on berry productivity. Preliminary analyses show the very strong influence of local environmental factors on berry production. In the year to come, a number of papers, contributions of the many graduate students involved in this network, are expected to be published in scientific journals. This research will fill a gap in the literature as much of the current references on the subject are from studies conducted in Scandinavia.

Involving students in communities in environmental monitoring was one of our most important objectives, as this is seen to be an effective method for developing an interest in science and the link to TEK-IQ among northern Youth. As a result of our work, the Avativut program was developed and Kativik School Board for Nunavik has adopted our methods and project ideas for monitoring berry production, snow, ice and permafrost. We hope to expand this type of program to the other Inuit territories, beginning with Nunavut.

We pursue our efforts in the decolonization of Science and Science Education by working more closely with our Inuit partners and by adapting our methods and educative material to the local context and students' attitudes and interests.

The books to be published this year will constitute a legacy of Inuit perception of climate and environmental change and will be unique educational tools, both in the North and in the South.

Through our growing experiences, enhancing opportunities for Youth and Elders in northern communities to spend time on the land together, either through camping excursions or day trips to important sites, can stimulate and enhance knowledge transfer and deepen connections between generations.

While there is still much to learn about the basic ecological relationships and potential cultivation techniques, there is an economic potential in growing and processing *Rhodiola rosea* in Nunatsiavut communities.

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Inuit and Northern Governments and Organizations:

- Kativik School Board (Nunavik)
- Institut culturel Avataq
- Northern Village of Kangirsujuaq
- Kangirsujuaq Land Holding Committee
- Northern Village of Quaqtaq
- Northern Village of Kangirsualujjuaq

- Northern Village of Umiujaq
- Hamlet of Pangnirtung
- Hamlet of Pond Inlet
- Nunatsiavut Government
- Nain Inuit Community Government
- kANGIDLUASUk Student Intern Program
- Labrador Inuit Development Corporation
- Nunavut Parks
- Nunavut Department of Education
- Nunavut Department of Environment
- Nunavut Department of Culture, Language, Elders and Youth
- Nunavut Inuit Heritage Trust
- Hamlet of Baker Lake
- Hamlet of Kugluktuk
- Hamlet of Igloolik

Academic Institutions:

- Arctic College in Iqaluit (Nunavut)
- Nunavut Research Institute
- Memorial University of Newfoundland; Labrador Institute
- Université de Montréal
- Jardin Botanique de Montréal/ Institut de recherché en biologie végétale
- Université du Québec à Trois-Rivières
- University of British Columbia
- Centre d'études nordiques
- Institut national de la recherche scientifique, Centre
- Eau, Terre Environnement
- Université Laval

Government Agencies and Funding Bodies

- ArcticNet NCE
- Parks Canada Agency (Torngat Mountains National Park; Sirmilik National Park)
- Health Canada
- Aboriginal Affairs and Northern Development Canada (NSTP)
- NSERC
- FQRNT
- CANPOLIN
- Natural Resources Canada (Polar Continental Shelf Program)
- NovaScience (MDEIE, Gouv. Québec)
- Agence spatiale canadienne (Gouv. Canada)
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Industrial Partners

- First Air, Air Inuit, Air Creebec
- Agnico-Eagle Mines

PUBLICATIONS

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HIGH ARCTIC HYDROLOGICAL, LANDSCAPE AND ECOSYSTEM RESPONSES TO CLIMATE CHANGE

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ABSTRACT

Water is crucial for northern communities and ecosystems and plays a vital role, in conjunction with climate and permafrost, in the morphology and stability of arctic landscapes. To determine the impacts of climate change on freshwater quality and availability in the High Arctic, we created a watershed and landscape ecosystem observatory. The research is conducted primarily at the Cape Bounty Arctic Watershed Observatory (CBAWO) on Melville Island, near the Nunavut/NWT border, with additional work at Polar Bear Pass on Bathurst Island and the Apex River, Baffin Island. Research will investigate how climate change will affect rivers, permafrost, soils, vegetation, greenhouse gas emissions and the release of contaminants into High Arctic rivers, lakes and ponds. Our integrated watershed network will provide an unprecedented understanding of the sensitivity and anticipated future effects of climate change to the High Arctic water, permafrost and ecosystem. By closely integrating related water and ecosystem process studies, this project will identify key environmental and societal vulnerabilities. Our goal is to develop impact models to assess linkages between anticipated environmental change and possible adaptations by communities and government agencies (clean water supply and ecological integrity) and industry (resource extraction, infrastructure protection).

KEY MESSAGES

- With a full decade of hydrological measurements at CBAWO and additional measurements at Polar Bear Pass and the Apex River, we have now developed a strong understanding of the control of changing climatic conditions on runoff.
- Late season runoff is particularly sensitive to changing rainfall, soil moisture and ground ice melt.
- Subsurface flow plays an important role during the late summer period and may have a critical role in regulating stream flow, and to a lesser extent ponds.
- Summer pond levels are dominated by the interaction of summer precipitation inputs versus evaporation losses.
- Recovery from 2007-8 permafrost disturbance continues with divergent impact surface water pathways and quality in terms of sediment erosion and dissolved materials.
- Permafrost-derived organic matter, which is being released from disturbances into rivers and affecting the organic geochemical signature.
- Fiver years following permafrost disturbance, significantly higher concentrations and fluxes of nitrate (NO_3^-) are observed in disturbed catchments relative to adjacent undisturbed catchment runoff.
- Stable isotopes of NO_3^- indicate that the enhanced nitrate from the disturbed watersheds is microbially derived. This additional net export of mineralized NO_3^- indicates disturbances likely enhance both nitrification rates, and diminish catchment NO_3^- uptake and retention.
- Concentrations of both CO_2 and CH_4 are low in the surface waters of East and West Lakes, while concentrations are higher in the bottom waters, suggesting that there is biological decomposition of organic matter in the sediments of these cold lakes.
- Mean total mercury concentrations in landlocked arctic char were significantly greater in West Lake, which is impacted by permafrost disturbances within its catchment, compared to relatively unimpacted East Lake.
- Despite continued inputs and catchment disturbance no significant time trend of total mercury concentrations in landlocked char was found for 2008 to 2014 in West or East Lake.
- The net carbon balance of polar semi-deserts is strongly linked to vegetation cover and air temperature, making it feasible to quantify net carbon exchange based on remotely-sensed and climatic data.
- Changes in growing season temperature appear to trigger the switch from net carbon loss to net carbon uptake in polar semi-desert ecosystems.

OBJECTIVES

Rationale

Our ArcticNet program capitalizes on the success of the highly integrated research conducted at the Cape Bounty Arctic Watershed Observatory (CBAWO), Melville Island, Nunavut (Figure 1). The CBAWO represents the only High Arctic observatory of its kind: integrating studies of climate change impacts on terrestrial, aquatic and hydrological processes at the watershed scale. One of the key developments that shaped the direction of the research at this site for the current ArcticNet funding period was the permafrost disturbances (active layer detachments) that occurred between the end of summer 2007 and summer 2008. Since this time our team has turned its attention to evaluating the impact these disturbances have had on various processes. Therefore, overall the proposed research aims to address the ramifications of varying degrees of permafrost disturbance on

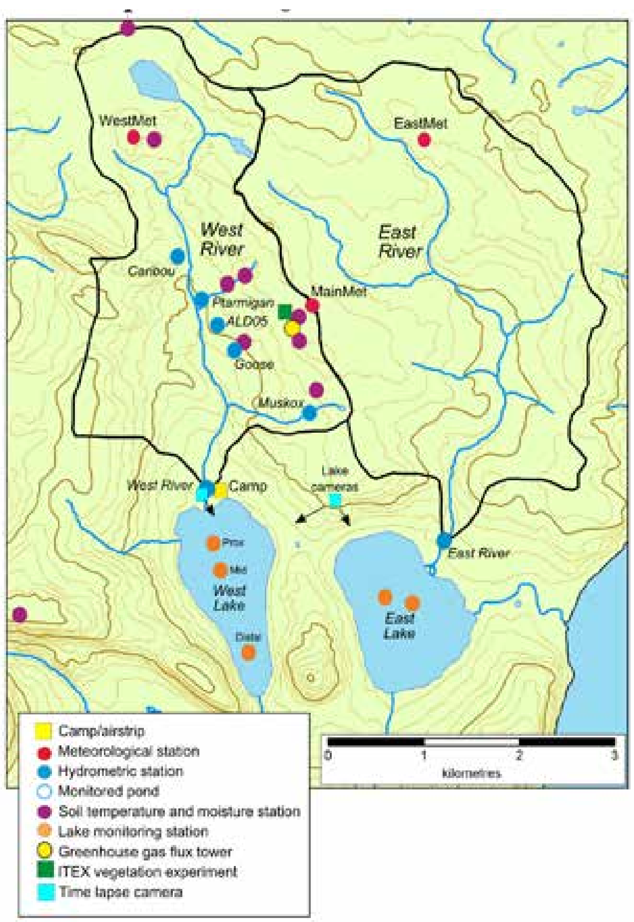

Figure 1. Map showing the Cape Bounty Arctic Watershed Observatory (CBAWO).

carbon budgets, microbial activity, and nutrient and contaminant cycling in High Arctic watersheds, as well as investigating the processes and response of High Arctic landscapes and surface waters to climate change.

Our findings over the last two years increasingly point towards the hydrological and biogeochemical significance of (i) both thermal and geomorphic changes to permafrost (and active layer) and (ii) changing precipitation regimes. We have observed physical and chemical changes in lake and river chemistry that suggest late summer warming and precipitation alter hydrological flow (including subsurface connections) and generate new sources of runoff that have important biogeochemical consequences.

The 2015 field research will refine our understanding of links between changing permafrost conditions and precipitation on the hydrological surface and subsurface flow paths, carbon and nitrogen budgets (aquatic and atmospheric), the structure and decomposition of organic matter, and contaminant cycling in the terrestrial and aquatic systems in High Arctic watersheds. We have adopted an alternate year strategy for full hydrological monitoring at CBAWO due to personnel and logistical limitations, and plan targeted sampling and instrumental measures in alternate years. After a highly successful full season in 2014, our 2015 season will focus on key sampling to advance our fundamental understanding of processes and interconnections in the watershed system.

Additionally, after two years of initial research at the Apex River near Iqaluit, NU (Figure 2) we plan to scale this research program up through greater integration of our team (Treitz, Scott, Humphreys) and with new collaborators (Richardson, Shirley, Franssen). The Apex River presents a scientifically compelling watershed research program in a context with demonstrated strong community and stakeholder interest. We anticipate our efforts in this portion of the project will continue to address key water security questions, and will also build capacity for research and community engagement with respect to water and terrestrial ecosystems.

Specific objectives in 2014-15 were to:

- Investigate subsurface flow pathways in soil and establish the connections between soils and surface waters.
- Determine the sources of organic matter in rivers and streams to evaluate if permafrost-derived organic matter is being released into biogeochemically active areas of the ecosystem via active layer detachments.

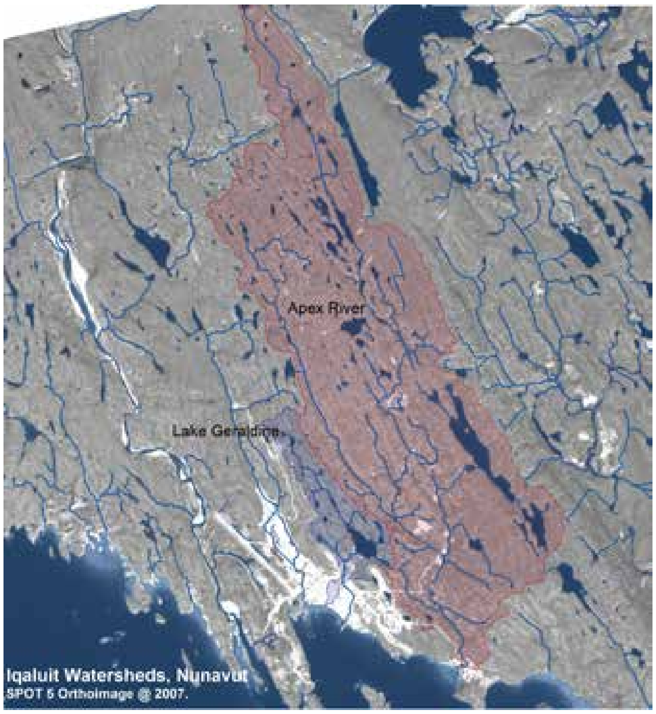

Figure 2. Map showing the Apex watershade near Iqaluit.

- Examine the potential for permafrost-derived organic matter to enter downstream lake systems.
- Quantify the impacts of climate change on the net exchange of two greenhouse gases (GHGs: CO_2 and CH_4) from aquatic landscapes at Cape Bounty.
- Determine zones of production and decomposition activity in high Arctic lakes at Cape Bounty.
- Continue to determine mercury and trace elements in landlocked Arctic char to develop a time series from which impacts of permafrost disturbances in the catchment of West Lake can be assessed.
- Continue to determine tributary inputs of mercury and methyl mercury to West and East Lake at Cape Bounty as part of an assessment of mercury biogeochemistry at Cape Bounty.
- Examine the impacts of year-to-year variability in weather on seasonal CO_2 exchange between the tundra and the atmosphere.
- Determine the factors controlling the net exchange of CO_2, CH_4, and N_2O at various spatial and temporal scales and develop scaling mechanisms to extrapolate site-specific results to larger areas.
- Expand the stream, lake and precipitation sampling program at the Apex River watershed so as to better determine the key hydrological controls and sensitivities of runoff in this watershed.

INTRODUCTION

Human-induced climate change is altering polar ecosystems at unprecedented rates. 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. 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, soil erosion, net primary production of tundra vegetation and greenhouse gas exchange with the atmosphere. Collectively, these processes have important impacts on surface waters and landscapes. However, there is considerable scientific uncertainty, and few comprehensive datasets to assess the potential impacts of climate changes on water resources in the High Arctic. Predicted warming has already begun and was exemplified by 2007, the warmest melt season on record, which resulted in extensive permafrost degradation in many areas in the Arctic. As a result, the need is great for integrated research programs in the Arctic to quantify the changes in watershed processes and ecosystem response.

This research has been conducted at the Cape Bounty Arctic Watershed Observatory (CBAWO) on Melville Island, on the Northwest Passage near the Nunavut/

NWT border. Since 2003 (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 (Figure 1). The multidisciplinary research team has diverse expertise that has allowed them to develop an integrated approach to resolving uncertainties in the response of High Arctic watersheds to climate change. Sustained research at CBAWO has reached a decade, providing key insights into hydrological, terrestrial and atmospheric processes in the High Arctic.

Our research group has also undertaken parallel and complementary research at Polar Bear Pass, Bathurst Island and in 2013 initiated a collaborative project with northern stakeholders on the Apex River, near Iqaluit, Baffin Island. These efforts are intended to transfer the knowledge gained by long term, integrated research at CBAWO to other areas of the Arctic and to work to address community and stakeholder knowledge needs for water management.

ACTIVITIES

Hydrological, limnological and related biogeochemical

Field activities extended from May 20-August 9 and focused on several key areas at CBAWO to refine our knowledge of hydrological, water quality and lake processes, including the continuation of multi-year data sets at the site. Field activities were closely coordinated by the research team to make efficient use aircraft and field personnel. Field sampling at the Apex River covered the period of February-November in collaboration with NRI and AANDC staff, with intensive sampling in June-July. No field activities were carried out at Polar Bear Pass due to the sabbatical by K. Young, but a number of research projects continued and are reported in the Results section.

Summer programs included a full season of hydrological, limnological and related sampling. In addition to the two main rivers at CBAWO, subcatchment streams and soils were sampled by Ph.D. student L. Ghimire, and a longitudinal water temperature and chemistry program was undertaken by M.Sc. student C. Bolduc. A longitudinal sampling of the West River was also undertaken for stream sediments (to replicate a similar program in 2013). Water column sampling and profiling was undertaken in both lakes to continue these long term records and lake sediment cores were recovered for detailed organic geochemical analysis by Ph.D. student D. Grewer.

At the Apex River, field research began with snow sampling in February-June, and systematic water sampling at stations in the catchment throughout the runoff period until freeze-up in November. Sampling was intensified for a eight week-interval when B.Sc. student E. Skaarup carried out detailed sampling of water chemistry and stable isotopes to determine different water sources, and to compare with similar data collected in a study from the previous year. Sampling continued with NRI personnel (J. Shirley) until freeze-up. S. Lamoureux also completed a second year of sampling a network of 20 lakes across the watershed for chemistry and stable isotopes for the purposes of determining changes in water balance in the watershed. The dissolved ion chemistry and stable isotope composition of the 2014 stream, rainfall, snowfall, lake samples are being analysed by undergraduate student L. Steer of his B.Sc. thesis project, which aims to characterise or chemically fingerprint the composition of the key components of stream discharge, in order to improve our ability to identify and quantify seasonal changes in water sources and pathways. Undergraduate student K. Burd is analysing the seasonal changes in the quantity and quality of dissolved organic matter in the 2014 samples from Apex River. The combined results from these undergraduate thesis projects will allow us to investigate how seasonal and downstream changes in hydrological inputs influence key water quality parameters, such as dissolved organic matter and nutrient concentrations.

Our previous work (published in Grewer et al., 2015) demonstrated that permafrost-derived organic matter was indeed entering the West River at the Cape Bounty Arctic Watershed Observatory (CBAWO). However, it remains unclear if this organic matter, which is rich in labile components, will degrade rapidly with time. To test this further, we have collected sediment and dissolved organic matters samples from the West River in the summer of 2013 and 2014. Samples from both 2013 and 2014 will be analyzed using a complementary, molecular-level approach. This included solid-state ^{13}C NMR analysis of whole samples and a targeted approach that included the analysis of specific organic matter components (various microbial- and plant-derived lipids, lignin-derived phenols, and microbial-derived phospholipid fatty acids). These methods allow for the quantitative determination of organic matter sources and stage of diagenetic alteration. After the organic geochemical analyses have been completed, we will also employ compound specific radiocarbon analyses to help compare temporal trends. From this work, we will have 3 years of detailed, organic geochemistry data that will provide unique insight into the biogeochemistry of hydrologic systems both spatially and temporally. The comparison of the dissolved and particulate (sediment) organic geochemistry will also serve to highlight differences in the sources and degradation of these two significant components of the watershed C budgets.

Grewer et al. (2015) also observed that permafrost-derived organic matter survived, for the most part, riverine transport into nearby lakes. As such, we will also investigate the organic geochemistry of lake cores, collected from the West Lake at Cape Bounty Arctic Watershed Observatory (CBAWO) in the summer of 2014. Radiocarbon analysis of previous cores, conducted by S. Lamoureux's research group, suggests that older carbonaceous materials are being deposited in the upper layers of the core. Thus, a molecular-level analysis will confirm that widespread permafrost melt, brought on by climate change, is altering the hydrological delivery of organic matter as well as the quality of organic matter in the Canadian High Arctic.

From under the ice in May, and throughout the open water season, dissolved GHG samples were collected from East and West lakes. Surface dissolved GHG samples were collected in East and West lakes to calculate the net ecosystem exchange of these GHGs with the atmosphere. We also did depth profiles of these GHGs in both East and West lakes to determine zones of production and decomposition.

Lake work also focussed again on collection and analysis of water from the lakes and their inflows during July 2014 for analysis of total mercury (THg) and methyl mercury (MeHg). Water was stored in amber glass bottles in heavy cardboard boxes. Landlocked arctic char were collected from East and West Lake August 1-4, 2014. 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^{o}C) for transport. Water and fish were shipped in Environment Canada (Burlington) in early August. THg and MeHg were determined at Environment Canada labs in Burlington, ON using standard U.S. Environmental Protection Agency analytical protocols. Mercury in (skinless) muscle was determined directly using a Direct Mercury Analyser while 31 elements determined by acid digest (nitric/HCl) and ICP-MS. Carbon and Nitrogen isotope ratios ($\delta^{13}C$ & $\delta^{15}N$) were determined by IRMS (EIL, U of Waterloo). Analysis of covariance of the THg data in char was used to assess trends over time using length or $\delta^{15}N$ or interactions with year in the model. Length and $\delta^{15}N$ adjusted least squared means were calculated.

Terrestrial ecosystem and element cycling

General circulation models predict significant changes in climate for the Arctic (IPCC 2013), including both changes in temperature and precipitation.

Global temperature records indicate that some of these changes have already occurred, with the Arctic showing some of the greatest positive temperature anomalies (Derksen et al. 2012). These changes are likely to cause changes in the spatial patterns of vegetation distribution, and also modify key environmental factors that control terrestrial biogeochemical processes. Research explores the key processes that control these biogeochemical processes at a range of spatial and temporal scales, and how these controls differ among key vegetation types. Our results are integrated into models that improve our ability to predict how the Arctic will respond to changes in climate that are already occurring.

We carried out measurements of biophysical properties and GHG exchange rates at various temporal and spatial scales, improving our understanding of the factors that control the net GHG balance of wet sedge meadows in the High Arctic. Measurements of net ecosystem exchange (NEE) of CO_2 and ecosystem respiration (Er) were made using ADC ACE autochambers at 6 locations in wet sedge with a sampling frequency of every 30 minutes. In addition, static chamber measurements of the same processes were made over a much larger area of wet sedge. Additional measurements of both CH_4 and N_2O production were made at these locations as well. Associated measurements of key vegetation properties were also made in collaboration with team member P. Treitz.

N. Scott continued to work on carbon exchange data from 2013 collected in polar semi-desert communities. These sparsely vegetated plant communities exhibit high spatial heterogeneity in vegetation cover, making it difficult both to collect appropriate field flux measurements and to scale them up in space and time. In a related project S. Jackson (B.Sc. student) explored the impact of enhanced temperature and snowfall on soil biogeochemical processes by measuring GHG exchange rates in our full factorial (temperature (2 levels) and snowfall (2 levels)) ITEX (International Tundra Experiment) installation. These data will be a good precursor to an intensive campaign in these plots in 2015.

In collaboration with E. Humphreys, we set up an eddy covariance system tower on June 11 to measure NEE over a mesic tundra area at very high frequency. The tower ran until July 29, giving us 48 measurement days for the 2014 growing season. These data are a continuation from previous years, and make up a five year record.

RESULTS

Hydrological, limnological and related biogeochemical

In 2014 we tested the hypothesis that subsurface flows deliver water to the rivers through both preferential pathways and contribute a measurable portion of baseflow in the rivers. M.Sc student C. Bolduc undertook detailed temperature profiles of the West River and sampling for water stable isotopes and chemistry at fixed stations throughout July. He noted a general downstream warming of the river on most occasions, but in some instances, temperatures cooled downstream, indicating contributions of cool subsurface water. Isotopic patterns confirm gradual inputs of water from subsurface sources as the mechanism rather than hyporheic (channel bed) interactions (Figure 3). These patterns are currently being compared to terrain data to determine precisely where inflows are located for future instrumentation and characterization. This work, in collaboration with J. Franssen (U. Montreal) represents a key new area of research at CBAWO. Undergraduate student J. Papernick is analysing the ion and nutrient data obtained from this study to investigate potential implications that subsurface water sources, or hyporheic exchange has on dissolved ion and nutrient concentrations.

Ongoing analysis of the impact of permafrost disturbance at CBAWO has demonstrated key

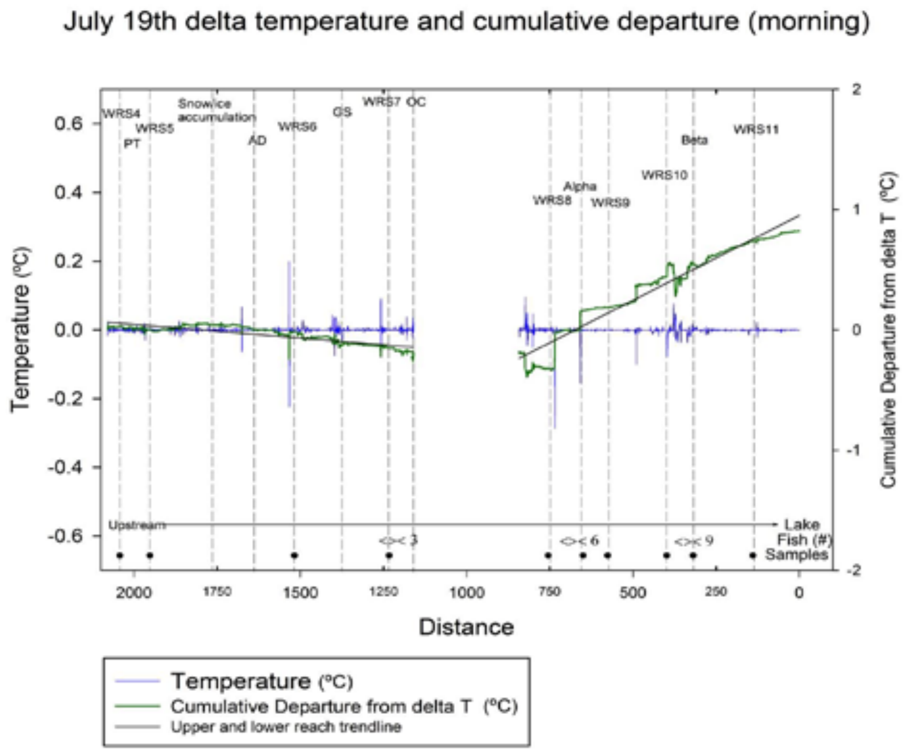

Figure 3. West River temperature delta and cumulative departure (morning) on July 19th.

distinctions between physical disturbance caused by localized slumps, compared to catchment-wide thermal perturbation caused by one or more years of warm conditions that result in deep thaw and changes in downstream water quality. Lafrenière and Lamoureux (2013) note that the impact of physical disturbance on downstream dissolved load is measurable and proportionate to the area of disturbance, while Lamoureux et al. (2014) not that the recovery of some disturbances has progressed more slowly than others. Results from CBAWO indicate that differences in geomorphology and hydrological connectivity result in divergent recoveries for individual disturbances, and it is hypothesized that these differences result in long term catchment heterogeneity of sediment erosion on the landscape (Figure 4). We continued to evaluate the runoff from a core set of subcatchments (Ptarmigan, Goose, ALD05) for this research theme and analysis of the 2014 data is currently underway by B.Sc student Papernick and Ph.D. student Ghimire. These results further provide important evidence for sustained water quality changes after a period (or single year) of permafrost perturbation, with implications for modelling and predicting downstream water quality. These results will aid in developing landscape based modelling approaches for sediment erosion and predicting downstream water quality changes, and natural variability constraints for baseline environmental data.

Sediment organic geochemistry from the West River suggests the addition of unaltered, plant-derived organic matter from disturbed sites along the subcatchment (Grewer et al., 2015). Figure 5 shows high concentrations of lipids at the headwater (UW1) and the disturbed sites (DS1-DS3). Long-chain alkanes are characteristic of plant-derived organic matter. Based on these results, we hypothesized that old plant-derived organic matter previously preserved in permafrost is entering the catchment through active layer detachments. Previous work by Lamoureux and Lafrenière (2014) also demonstrates that the organic

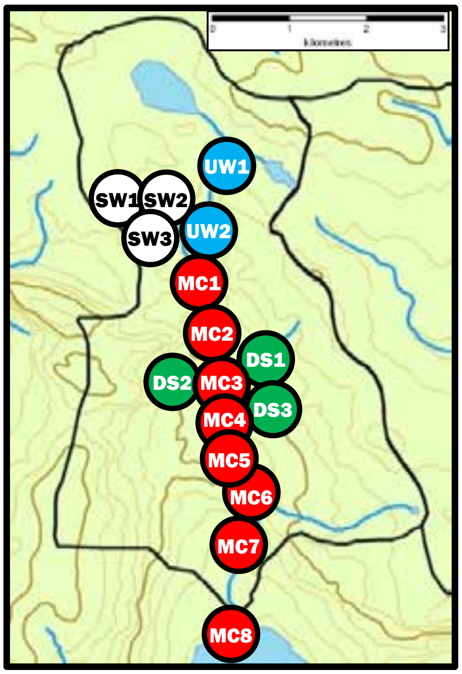

Figure 4. Catchment heterogeneity of sediment erosion on the landscape.

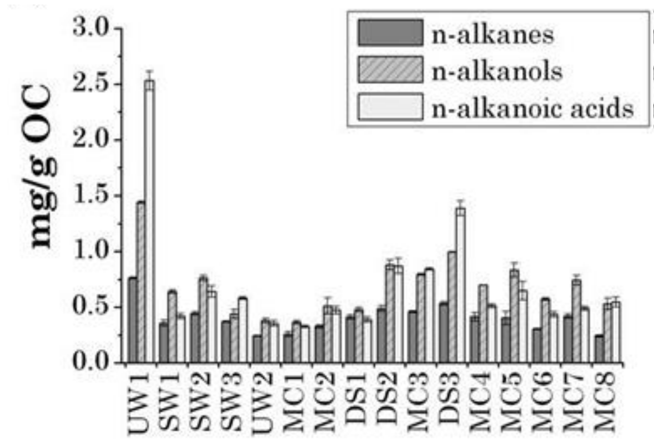

Figure 5. Distribution of aliphatic lipids in sediment samples from CBAWO.

matter from disturbed catchments is significantly older than OM from undisturbed catchments.

Solid-state ^{13}C NMR analysis similarly shows high concentrations of labile organic matter, consistent with plant inputs, entering the catchment at the headwaters and disturbed sites (Figure 6). Unaltered plant-derived organic matter is enriched in easily biodegradable substrates such as in carbohydrates and peptides which will result in a high O-alkyl signal in the ^{13}C NMR spectrum. The O-alkyl concentration increases near the headwaters and then decreases downstream, likely due to microbial degradation as the organic matter moves through the catchment. However, there are additional contributions near disturbed sites again suggesting that active layer detachments release old, unaltered plant-derived organic matter into the sub-catchment.

Recent studies examining the impact of disturbances on dissolved nitrogen fluxes indicate that the disturbances are likely leading to enhanced production of microbially produced nitrate (NO_3^-) in runoff (Louiseize et al., 2014). The enhanced nitrate concentrations were particularly high in the late season runoff (Louiseize and Lafrenière, submitted). These increases in NO_3^- fluxes were observed five years post-disturbance, indicating that the impacts of permafrost disturbance on nitrogen dynamics persist for several years. The enhanced release of microbially produced nitrate may be further evidence that that the disturbances, through the release of easily biodegradable organic matter noted above and elsewhere (e.g. Grewer et al., 2015; Paulter et al. 2011, Woods et al. 2010), serve to 'prime' these catchments for enhanced biological activity.

We also investigated the organic composition of sediment emerging on the land surface in the form of mud ejections. Organic geochemical characterization using organic matter biomarkers and NMR spectroscopy were used to characterize these samples. Our work shows that two samples (one from Cape Bounty and one from the Sabine Peninsula, Melville Island) are predominantly recalcitrant in nature and are consistent with the organic geochemistry of diagenetically altered materials found in the sub-surface. However, the second sample collected from the Sabine Peninsula also contains organic matter characteristic of unaltered plant-derived organic matter. Interestingly, all three mud ejections had unique organic matter geochemistry suggesting that

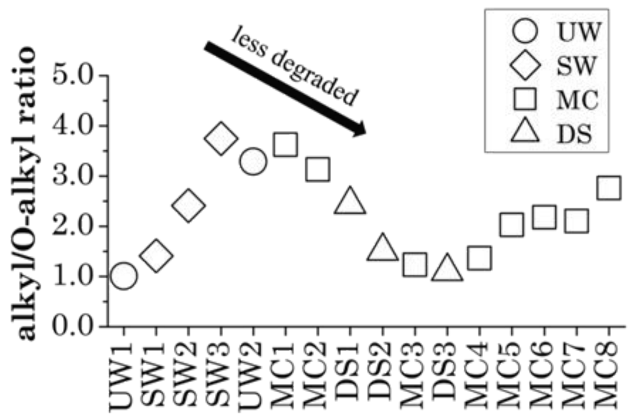

Figure 6. O-alkyl (labile) to alkyl (recalcitrant) ratio of organic matter components measured using solid state ^{13}C NMR.

these localized features are contribute distinct organic matter inputs into the surface.

Initial results from the Apex River project provide insights into climate change and hydrological impacts in a setting close to a large community and where residents use the river intensively for many activities. Iqaluit has substantially warmed since the late 1990s, particularly in the autumn months (Sept-November), resulting in a longer streamflow period. Initial analysis of stable isotopes in the river water indicate a consistent shift towards enrichment but further incorporation of water chemistry data is necessary to interpret potential changes in water sources in the catchment. Thee analyses are underway and we anticipate developing a 2015 field program to extend this research.

Research at Polar Bear Pass (Bathurst Island) to complement studies at CBAWO has focused on the hydrology of ponds and wetlands. Preliminary analysis of groundwater data (from 2007 to 2010) indicates that groundwater inflow in the post-snowmelt season (month of July) is not an important source of water to tundra ponds at PBP. Pond water levels in the summer period respond to rainfall inputs and losses due to evaporation (Young et al., 2014). Groundwater flow from wet meadows increases during wet seasons and declines during warm/dry seasons. During the wet season, groundwater flow is largely dominated by the pattern of rainfall (duration/intensity/amount). In drought periods, the aquifer characteristics (thickness of the water zone, topographic gradient, hydraulic conductivity) define the flow pattern. Pond water budget studies (2007, 2008 and 2009) indicate that in July, groundwater inflows are not important but inputs (rainfall) and losses (evaporation) control pond storage (i.e. water table fluctuations). This occurs whether it is a warm/dry season or a cold/wet season. A Polar Bear Pass DEM has been finished thanks to the efforts of Kelly To (B.Sc student McMaster U.). Additionally, a database of stream/pond temperatures (2007 to 2013) has been finalized with analysis of results is ongoing.

In 2014, we continued to collect systematic water column profile data, including CTD casts, and samples for water chemistry and dissolved gases. Concentrations of CO_2 are generally low in both East and West lakes. However, concentrations of CO_2 increase at depth in West and East Lake, suggesting higher rates of decomposition in bottom sediments there. However, the increase in bottom concentrations of CO_2 are much greater in West Lake relative to East Lake. Concentrations of CH_4 are below detection throughout the West Lake water column, but detectable throughout the East Lake water column.

Water column concentrations of THg continued to be higher in West Lake. Including the most recent samples, average THg concentrations in West Lake are 2.2±2.4 ng/L compared to 0.7±0.4 ng/L in East Lake. High concentrations of THg have been found in particulate THg (7.1-9.4 ng/L) at the bottom of the water column in West Lake, which are indicative of sinking particles and/or resuspension. Methyl Hg concentrations continue to be extremely low and comparable in the two lakes (0.01±0.01 ng/L in both). Arctic char collections from East and West Lake now extend over the period 2008 to 2014. $\delta^{13}C$ in char muscle was consistently more depleted in East Lake compared with West Lake indicating carbon in West Lake fish is of more terrestrial origin. $\delta^{15}N$ was significantly higher in East Lake char (mean±95% CI, all years, 11.22±0.12‰ vs 10.02±0.20‰) suggesting differences in food sources (Figure 7a). Mean $\delta^{15}N$ values from 2008 to 2013 did not change significantly in either lake. Condition factors (cg/cm^3) in the char have increased in East Lake while continuing to decline in West Lake (Figure 7b). West Lake fish were generally longer for a given weight. CFs of ~0.7 are typical of char in other high Arctic lakes while values <0.6 imply a low food supply or other stressors. Mean THg concentrations in West lake char continue to be significantly greater than those in East Lake except in 2009 when char were feeding on more pelagic carbon (Figure 8). Adjustment for trophic level of the char using $\delta^{15}N$ to take into account differences between lakes had minimal overall effect compared to using length adjustment for the same results.

Terrestrial ecosystem and element cycling

In recent years, we have conducted field experiments and analysed remote sensing data to determine the potential for: (i) high spatial resolution optical data for characterizing arctic vegetation composition and biophysical variables (Laidler et al., 2008; Atkinson and Treitz 2012; 2013); and (ii) synthetic aperture radar (SAR) data for characterizing surface roughness (Collingwood et al., 2014), vegetation (Collingwood et al., 2014); and surface moisture (Wall et al., 2010; Collingwood et al., in prep.). This body of work has demonstrated great potential for monitoring vegetation response and moisture regimes of High Arctic environments through a changing climate at watershed scales. To date, we are not aware of any other researchers examining the linkages between high spatial resolution satellite data and arctic vegetation composition, structure and function in the Canadian High Arctic for extension to landscape and regional scales. Our field campaigns have been extensive, are integral to our understanding of vegetation responses to environmental change, and are critical for scaling up to local and regional scales using satellite remote sensing data. In addition, specific to the Arctic and permafrost environments, we are extending our analysis to include change detection, particularly in the context of hazard susceptibility and permafrost degradation (Rudy et al., 2013).

In 2014, Treitz's research group conducted two field studies at the Cape Bounty Arctic Watershed Observatory (CBAWO) (Figure 9). Nanfeng Liu, a PhD candidate at Queen's University, collected detailed field data (i.e., percent vegetation cover (PVC) and normalized difference vegetation index (NDVI) data) for three vegetation communities at Cape Bounty. He sampled three plots (300 m x 300 m) to investigate the manner in which these biophysical variables scale-up from high spatial resolution field and satellite data

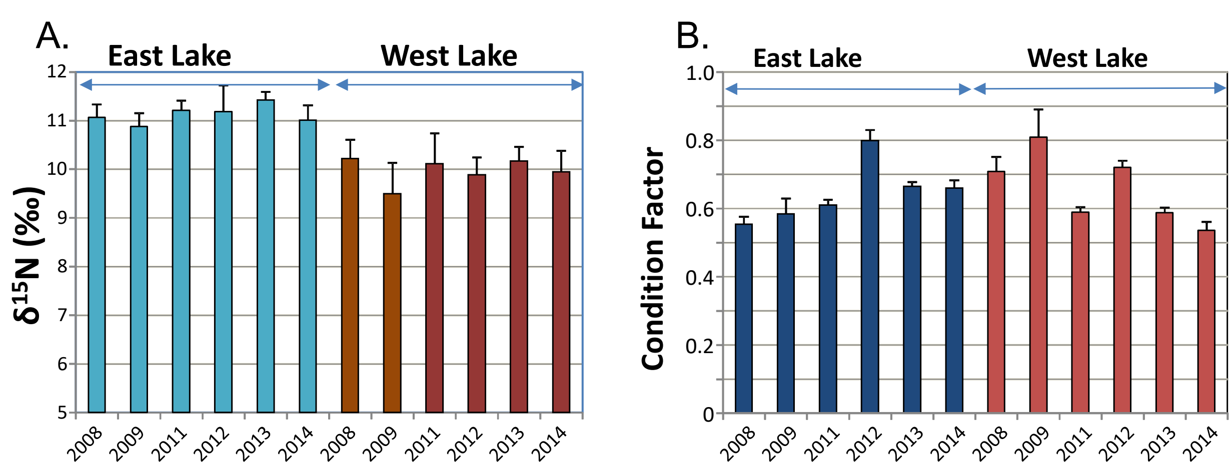

Figure 7. A. Nitrogen isotope ratio ($\delta^{15}N$) and (B), condition factors for arctic char in East and West Lakes, 2008-2014.

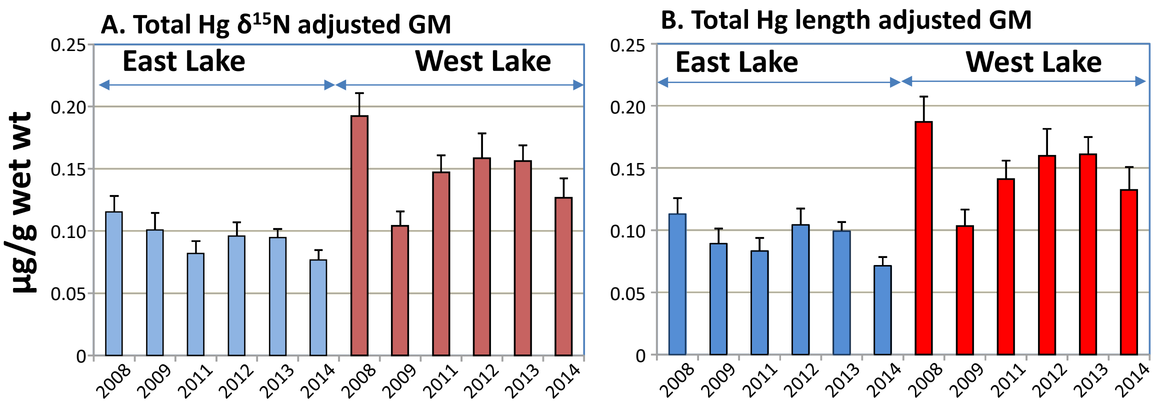

Figure 8. Geometric mean (± SE) concentrations of THg in muscle of Arctic char from East Lake & West Lake. A. Adjusted using $\delta^{15}N$ based on analysis of covariance model, B. Adjusted using length.

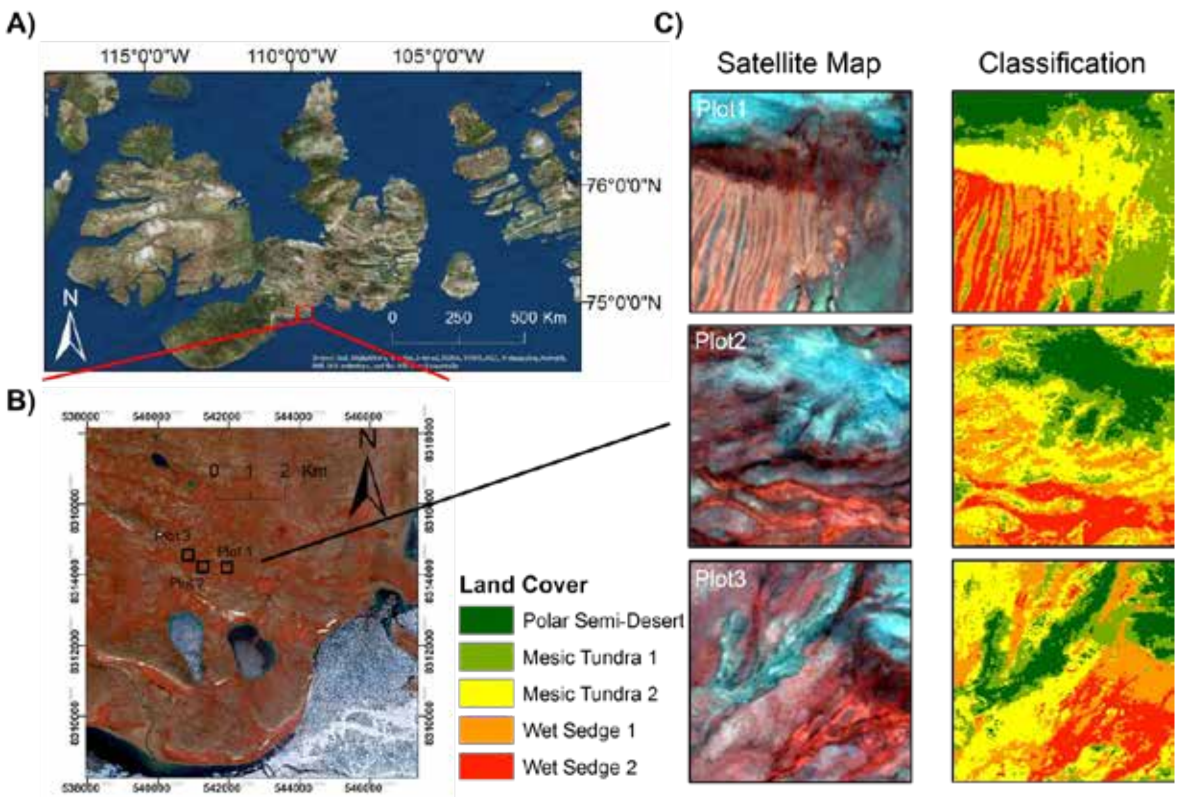

Figure 9. Cape Bounty Arctic Watershed Observatory (CBAWO) (panel a-b) and three sampling plots (panel c) on Melville Island, Nunavut, Canada. In panel b, the WorldView-2 imagery of Cape Bounty, acquired on July 12th, 2012, is displayed as a colour infrared composite image with bands 7 (shortwave infrared), 3 (red), and 2 (green). Black squares (panel b) represent three MODIS-pixel-scale (300 m x 300 m) plots within which field digital photographs were collected. Panel c illustrates high spatial resolution satellite data and classification maps of the three plots.

(i.e., WorldView-2) to intermediate (i.e., Landsat) and coarse resolution satellite data (i.e., MODIS) (Figure 9). He sampled these plots over an eight week period in order to capture the phenological changes occurring in these vegetation communities over the growing season. He is currently processing detailed NDVI field photographs to derive PVC by species group. In order for us to understand field level processes, we need to examine these processes at very high spatial (and temporal) resolutions. Further, in order to model these variables and processes over large spatial scales we need to understand how to scale-up from the detailed measures to coarse spatial resolution satellite data.

MSc candidate Amy Blaser spent the summer of 2014 measuring carbon dioxide (CO_2) exchange rates in wet sedge communities at the CBAWO. Her research explores the key factors regulating spatial and temporal patterns of ecosystem carbon exchange for wet sedge vegetation communities; these communities are the most productive vegetation communities in the High Arctic. Automated and static CO_2 exchange systems (Figure 10, 11) recorded CO_2 exchange from June to August, 2014. Automated systems measure carbon exchange at 30 minute intervals, but are limited to only six locations. Static chamber measurements are used to explore carbon exchange rates over larger areas. In conjunction with these measurements, time-series NDVI images were collected to quantify the phenological stage of the community through the growing season. Net ecosystem exchange (NEE) measurements indicate carbon uptake through photosynthesis, and NEE rates differed in spectrally separable 'wet' and 'dry' sedge areas (-0.33 and 0.01 $\mu mol\ m^{-2}s^{-1}$ means respectively; $p<0.001$). NDVI measurements captured spring greening and peak summer biomass, and will likely be a critical variable for modelling CO_2 exchange. Ms. Blaser is currently deriving predictive models of ecosystem carbon fluxes using NDVI and environmental measurements as predictors of carbon flux. This will allow us to evaluate the drivers of CO_2 exchange in these communities–spatially and temporally–and facilitate predictions of NEE based on NDVI and/or other biophysical variables.

In addition to carbon exchange measurements, we also carried out measures of CH_4 and N_2O exchange at the spatially extensive sites. These data will allows quantification of the key controls over total GHG fluxes for these dynamic wet sedge communities.

M.Sc candidate Emma Buckley is in the final stages of writing up her thesis research. She spent the summer of 2013 collecting CO_2 flux data for polar semi-desert vegetation communities at the CBAWO. While studies across latitudinal gradients in mesic tundra have shown decreasing levels of net ecosystem exchange

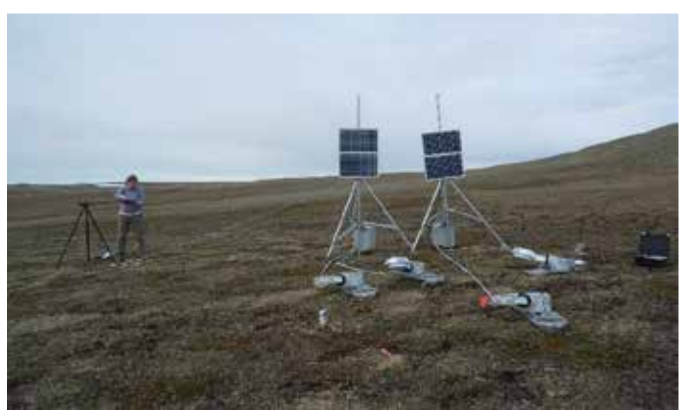

Figure 10. Static chamber system used to measure carbon exchange rates. Automated chamber systems measuring carbon exchange rates every 30 minutes.

Figure 11. Static CO_2 measurement chamber measuring NEE (photo credit: Emma Buckley).

(NEE) at more northern sites, little work has explored the factors regulating NEE in the polar semi-desert, a vegetation community which is widely distributed across the High Arctic and exhibits high spatial variability in vegetation distribution. Ms. Buckley deployed eight ADC Automated Carbon Exchange (ACE) systems (Figure 12) to quantify the contribution of the polar semi-desert plant community to the landscape-scale NEE. As polar semi-desert plant cover varies at relatively small spatial scales, the chambers were distributed between vegetated areas (18-51% cover) and bare soil. In July 2013, NDVI (Normalized Difference Vegetation Index) data were collected and compared to estimates of percent vegetation cover within the polar semi-desert. NDVI varied from -0.12 to 0.31, with the highest values occurring at vegetated sites and low values occurring on bare soil. Percent

Figure 12. Automated CO_2 chambers with transparent and opaque covers (photo credit: Neal Scott).

vegetation cover and NDVI correlated well at peak biomass ($R^2 = 0.96$) (Figure 13). We found that NEE is driven by variability in several biophysical factors for polar semi-desert communities, and the factor that best predicts NEE will differ throughout the growing season. In the early season, respiration drives NEE, and air temperature is the strongest predictor (R^2 = 0.23 to 0.55). During the warmer part of the season, photosynthesis dominates NEE, and photosynthetically active radiation (PAR) becomes the best predictor (Figure 14). Our results suggest a threshold temperature above which photosynthesis dominates NEE in polar semi-desert plant communities. Longer growing seasons, if associated with higher temperatures, would increase net carbon uptake and storage. NEE correlated well with vegetation cover ($R^2 = 0.96$) later in the season (Figure 15). These relationships will be critical for quantifying NEE in polar semi-desert communities using remotely-sensed data.

In addition to work in the wet sedge community, we carried out another series of measurements of both NEE and total GHG production at our ITEX installation. Preliminary results found significant differences in NEE, with rates of NEE being higher in the enhanced snowfall treatments compared to no

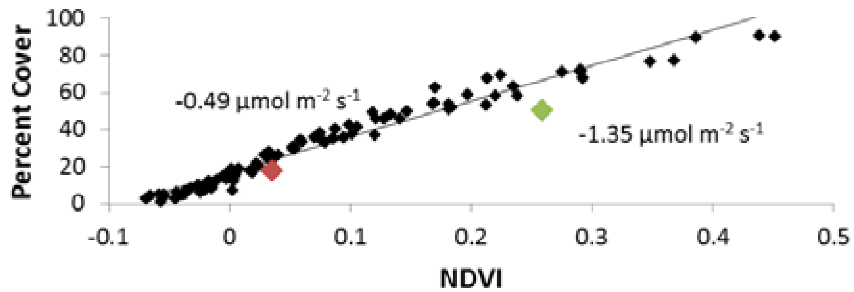

Figure 13. Relationship between NDVI and % vegetation cover in polar semi-deserts over large transects. Green and Red points represent sites where flux measurements were made (with associated average fluxes at the end of the growing season).

enhanced snowfall. This likely relates to differences in soil moisture that persist after snowmelt is complete.

EH Results from the eddy covariance tower showed that 2014 was one of the coolest years we have had since starting data collection at the CBAWO. The end result was that the ecosystem remained largely a source of carbon throughout the time that we made measurements (Figure 16). This is one of the first years that we have observed this over the entire growing season.

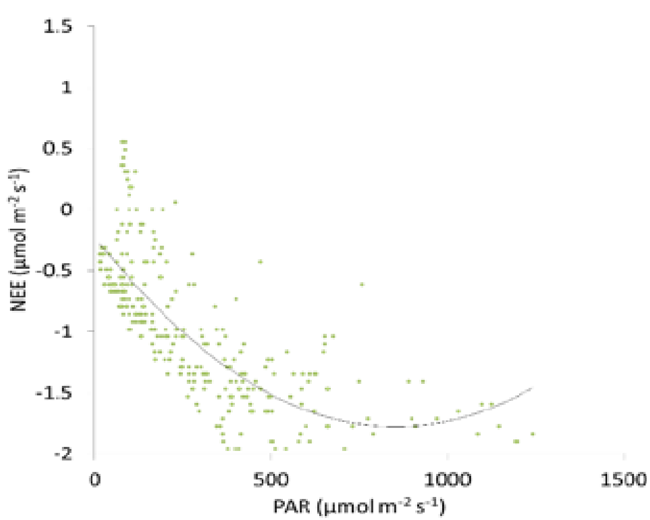

Figure 14. Relationship between PAR and NEE at end of growing season.

Apex Watershed

M.Sc student L. Kjikjerkovska has been evaluating the sensitivity of discharge in the Apex River to climate, using climate records and discharge records form the Water Survey. To date the results of this research indicate that total average discharge and flow duration in the Apex River have increased over the period of record (1973-1995, 2003-2013), while baseflow, or seasonal low flow volumes have decreased. Results of sampling from 2013 also highlight the importance of subsurface water as a source of runoff in late summer and fall, and also indicate that autumn rain events can make significant contributions to the overall seasonal discharge in the Apex River.

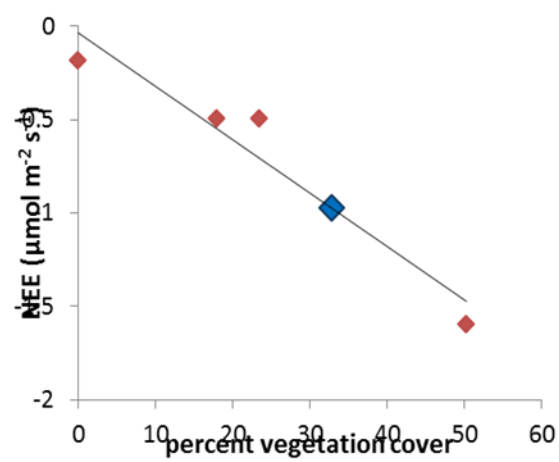

Figure 15. Relationship between percent vegetation cover and NEE at end of growing season.

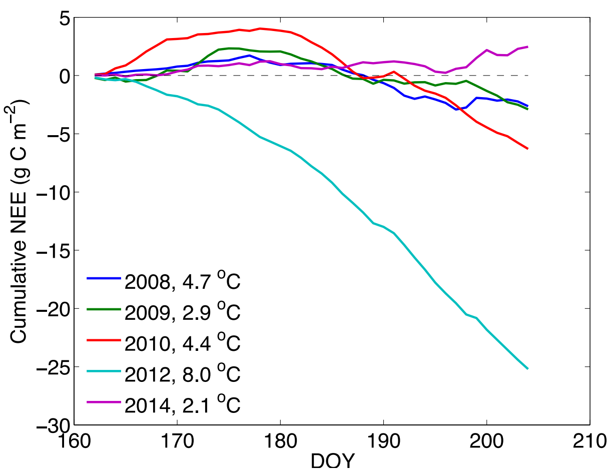

Figure 16. Cumulative Net Ecosystem Exchange of CO_2 (NEE) and average air temperature at the Cape Bounty flux tower between June 11 and July 24 of each year. When the final NEE is negative, the tundra is either a very small net sink for CO_2 (2008, 2009, and 2010), a small net sink (2012). In 2014, the tundra was a small net source of CO_2.

DISCUSSION

Hydrological, limnological and related biogeochemical

Hydrological research at CBAWO has revealed considerable insights into the impact of short term permafrost disturbance in the High Arctic, and the longer term impact this disturbance has on downstream sediment and dissolved loads (Lafrenière and Lamoureux, 2013, Lamoureux and Lafrenière, 2014, Lamoureux et al., 2014, Louiseize et al., 2014). This knowledge will be particularly important for the development of realistic watershed water quality models to predict future responses to projected climate changes, and will substantially extend first efforts to model sediment load (Lewis and Lamoureux, 2010) in this large region. Continued refinement of subsurface pathways research (such as the work by M.Sc student C. Bolduc) will begin to address key questions about how water quality evolves on the land and how changes in summer thaw depth will likely influence water quality.

This research at CBAWO has resulted in new efforts at the Apex River to transfer knowledge from ArcticNet research to address community interests and concerns about climate change impacts on water. While our efforts at Iqaluit have been underway for two years, with much of our effort directed at building partnerships and collaborations with NRI, AANDC and the City of Iqaluit, we anticipate that the key hydrological research questions addressed by these two watershed programs will advance the state of knowledge of watershed hydrology in the Canadian Arctic and will contribute to better water management in the region.

Our recently published study (Grewer et al., 2015) provides evidence which strongly suggests that translocation of organic matter from permafrost soil into a downstream hydrological system may be occurring as a result of active layer detachment events. Additionally, we observed that more recalcitrant organic matter may become vulnerable to degradation upon recovery and microbial priming in active layer detachment regions. Moreover, these fresh organic components may have already experienced degradation during transport into fluvial sediments. This supports studies that suggest older organic matter from deeper permafrost soils may exhibit greater lability. This enhanced lability may support increased microbial activity, thus accelerating the degradation of the permafrost-derived organic matter as the system recovers. However, the heterogeneity of sedimentary organic matter makes it difficult to differentiate between young and old pools of carbon. Hence, investigations using compound specific radiocarbon analysis of organic matter components should test this hypothesis and provide a more succinct framework regarding the nature of permafrost-derived organic matter released by active layer detachments. Future studies will also examine samples collected in subsequent years to examine temporal trends with respect to organic matter composition.

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.

Concentrations of CO_2 are higher in the bottom waters of East and West Lakes, clearly showing that there is biological decomposition of organic matter in the sediments of these cold lakes producing these CO_2 and consuming O_2. The different balance between CO_2 and CH_4 in East and West lakes suggests that East Lake might be more oxygen limited than West Lake.

Our preliminary conclusion from the extensive long term investigation of mercury in the lakes at Cape Bounty is that increased total Hg inputs into West Lake due to permafrost disturbance in its catchment have resulted in higher concentrations of Hg in char in that lake. The higher mean Hg concentrations in West Lake char were consistent with higher unfiltered THg concentrations in the West River and in West Lake, extensive permafrost disturbance in the West watershed and seasonal anoxia in that lake. Despite the higher THg inputs, no significant increase (or decrease) in Hg concentrations in the char were found over the period 2008 to 2014 in either lake. In some respects these results are a good news story for high arctic communities that may utilize landlocked char as part of the local subsistence fishery. On the other hand the declining condition factor is a concern over the long run because the fish may have difficulty feeding in West Lake's turbid waters and reproduction could be affected. Continued monitoring of the fish and waters in the lakes will help to address these questions.

Terrestrial ecosystem and element cycling

Globally, data from 2014 show that temperatures are warming in the Arctic, and results from other sites show changes in precipitation patterns. These changes will result in changes to the distribution and abundance of different vegetation types in the high Arctic. Our terrestrial research explores how these changes are likely to influence the net GHG balance of terrestrial ecosystems in the region, and whether these changes will have positive or negative feedbacks on the global climate system. These changes in vegetation will interact with changes in permafrost and landscape stability. At present, models of the arctic carbon balance often are parameterized assuming a single vegetation type, yet our results over the past few years suggest significant differences in the processes controlling net carbon exchange in the different vegetation types. In order to understand how future changes in climate will impact the region, we need to understand the different processes in the different plant community types, and develop ways to scale local studies to the broader arctic region. Linking ground-based measurements with remotely-sensed data provides one possible mechanism for monitoring these changes over large areas.

Our field research has shown that it is possible to quantify the high spatial variability of vegetation in polar semi-deserts, and how it impacts the net carbon balance in this community type. By linking our field measurements to various biophysical variables, we can capture seasonality in a single model that incorporates the key biophysical variables (e.g. NDVI, air temperature, PAR). We are also learning about the effects of enhanced snowfall on carbon exchange processes; our results suggest these changes do alter carbon exchange by altering both phenology of vegetation and biogeochemical processes linked to soil moisture. Finally, and perhaps most importantly, our research is helping train the next generation of Arctic scientists and educating others about the fragility of the Arctic, and how it might respond to the changes that are already occurring.

CONCLUSION

Research at CBAWO, PBP and the Apex River represents an integrated effort to identify the impact of climate change on landscape and water processes in the Arctic. Through comprehensive field and leading-edge analytical approaches, this project has identified key direct and indirect impacts of climate change on the terrestrial Arctic system. Key outcomes contribute new knowledge to our understanding of the hydrology, geomorphology and ecology of the High Arctic, and provide substantial process linkages associated with material fluxes, cycling and fate. This

knowledge will be disseminated through conventional scientific literature and will also be integrated into the preparation of the IRIS reports for regions 1 and 2 that are currently underway.

Based on the success of this approach and interest by community stakeholders and decision makers, we have expanded this research to the Apex River near Iqaluit. This location has allowed our research to build northern collaborations and more closely meet and respond to the interests of northerners. Hence, we aim to continue our work at CBAWO and the Apex River to develop primary process knowledge and build baseline records in remote, pristine settings, while at the same time transferring our knowledge and experience to northern communities and decision makers.

ACKNOWLEDGEMENTS

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GROWTH VARIABILITY AND MERCURY TISSUE CONCENTRATION IN ANADROMOUS ARCTIC CHARR

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Bridging the Gap: Linking scientific and Inuit knowledge of Arctic Char for community-based monitoring
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Thermal habitat use by young-of-the-year Arctic charr and the sensitivity of young-of-the-year to fluctuations in their thermal environment
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Spatial and temporal trends of mercury concentrations in Dolly Varden (Salvelinus malma) in the Yukon Territory
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ABSTRACT

The project was designed to build on prior work that examined probable climate change related growth and contaminant impacts on land-locked populations of Arctic charr by extending the analysis to include important migratory and land-locked populations of Dolly Varden charr in the Yukon Territory. There is a notable lack of data for Dolly Varden charr, despite the importance of the species as a country food resource. Here we plan to use existing archival tissue samples to construct an historical spatial baseline for THg levels in Dolly Varden charr against which contemporary data can be compared to examine the impacts of climate change and development activities on current THg levels. Work will also be extended to include comparative examination of Dolly Varden charr in the Beaufort and a determination of where and how they function in Beaufort Sea foodwebs likely to be affected by oil and gas exploration activities. The project will also continue important partnering work begun with Nunavik Research to examine the marine life-history phase of Ungava Arctic charr introduced into a previously unoccupied river system. Previously PIT-tagged fish have begun to return in numbers and we are now able to estimate annualized marine growth and compare that growth to monitored water temperatures as a means of estimating site-specific growth temperature relationships using oxygen stable isotope methods. Obtained field results are compared to data gathered in Labrador through collaborations with Fisheries and Oceans Canada. Results and comparisons are critical for assessing the possible impacts of climate change Nunavik Arctic charr and understanding how overall availability of Arctic charr will respond to predicted climate changes. To further improve conceptual understanding of temperature-growth affects location-temperature tags will be inserted into Arctic charr and monitored via acoustic receivers to track temperature use in both the marine and freshwater environments. In concert with growth studies, the project has been monitoring the ecological impacts of Arctic charr introductions and found them to be negligible. This effort represents the first attempt to scientifically evaluate the consequences of northern ecosystem manipulation and has provided important data and insights for management purposes by showing it is possible to proactively manage Arctic charr stocks with minimal ecological consequences. Finally work continues on genetic typing of Arctic charr populations to improve our understanding of how climate change may impact the immunological capabilities of Arctic charr and their abilities to deal with new diseases and pathogens likely to be introduced into northern environments as a result of changing environmental conditions. All study generated information will contribute to the improvement of management abilities to make informed decisions about the risks associated with continued country food consumption in the face of changing conditions in the Arctic. The project also identifies key environmental indicators of changes in Arctic Char (*Salvelinus alpinus*) growth using both quantitative (ecological) and qualitative (Indigenous Knowledge) data by linking community-based monitoring, local expert Indigenous and ecological knowledge. Arctic Char is a staple subsistence resource for Inuvialuit on Banks and Victoria Islands in the Northwest Territories, Canada. In recent years, significant climate variability and change has been observed in the area, raising local concerns about how this variability will affect subsistence resources. Residents in local communities are the first to directly observe and report these changes and variability in local climate and the effects they have on their land, water and animals. Centuries of knowledge and observations about the environment and natural resources exist among Inuvialuit hunters and fishers. Local expert Indigenous Knowledge (IK) can complement our scientific understanding of environmental variability and change and its effects on Arctic species. Community-based monitoring (CBM) provides an opportunity to better understand the current status of Arctic species and can form the basis for understanding and preparing for future changes in Arctic species in light of projected climate variability and change. Using a mixed-methods research approach is one way in which ecological scientific and Traditional Knowledge can be brought together to complement one another and provide a more thorough understanding of northern fish species in a changing environment.

KEY MESSAGES

- Results of studies of mercury contamination in Dolly Varden charr were completed with the submission and defence of the MSc thesis by L. Tran (Variations in Northern Dolly Varden (*Salvelinus malma malma*) total mercury concentrations from the northwestern Canadian Arctic) from which a single paper has been published (Tran, L. Reist, J. D. and Power M. 2014. Science of the Total Environment - see completed research activities below) and two others have been submitted for publication review.
- L. Tran's M.Sc thesis showed that historical THg spatial trends for anadromous Northern Dolly Varden were determined from 10 populations in the Yukon and Northwest Territories sampled across a range of latitudes (67-69° N) and longitudes (136-141° W) between the years 1988-1991. Unadjusted mean total mercury (THg) concentrations ranged from 15 to 254 ng/g wet weight (ww). Length-adjusted THg concentrations were significantly different among sites, but were not related to latitude or longitude. Within and among populations, THg was significantly related to fork-length, age, $\delta^{15}N$, and $\delta^{13}C$, with the variation in THg found among populations being best explained by size. The data serve as an important baseline against which future changes in THg levels in this important subsistence fishery may be compared to determine the significance of any observed trends.
- To understand the importance of life-history type on THg, THg concentrations were measured in isolate, resident and anadromous Northern Dolly Varden from the Babbage River, Yukon Territory, Canada. Differences in mean THg concentrations were found starting at 22 ng/g ww in isolate, increasing to 56 ng/g ww in resident, and 108 ng/g ww in anadromous fish. The pattern is markedly different than that observed in other migratory charr species where anadromous fish typically have lower levels of THg. After adjusting THg to a standardized age and length, significant differences remained among the life-history types, with anadromous Northern Dolly Varden having the lowest THg concentrations. Trophic position was the most important factor in explaining observed differences among the individuals regardless of life-history types, with growth rate also contributing to explaining the variation among individuals. The contrast of higher absolute, but lower age and size adjusted THg levels in anadromous fish was explained by a combination of two counter-acting mechanisms, including: 1) a switch to feeding at higher trophic levels and the use of prey with higher THg concentrations in the marine environment that raises THg levels, and 2) somatic growth dilution that decreases THg as fish age and increase in size.
- Temporal changes in Northern Dolly Varden THg concentrations were assessed between periods 1986-1988 to 2011-2013 from the Rat (67° 46' 48"N and 136° 19' 12"W) and the Firth (68° 40' 12"N and 140° 55' 12"W) rivers in the northwestern Canadian Arctic. In the Rat River, mean THg ranged from 79 ng/g ww in 1986-1988 to 109 ng/g ww in 2011-2013, while in the Firth River, THg ranged from 126 ng/g ww in 1986-1988 to 178 ng/g ww in 2011-2012. After factoring in size, $\delta^{13}C$ and $\delta^{15}N$, THg increased significantly over time.
- Relationships between log[THg] versus fork-length and log[THg] versus $\delta^{13}C$ have remained constant over time in the Rat River, but not in the Firth River, while relationships between log[THg] versus $\delta^{15}N$ have remained constant in the Firth River, but not in the Rat River. Although increases in temperature coincide with increases in THg, the effects are not direct.
- Studies of countergradient variation (CGV), defined as genetic variation that counteracts the negative influences of the physical environment, minimizing phenotypic variability along a gradient, in Arctic charr demonstrated patterns

consistent with CGV, where northern populations demonstrated faster growth rates compared to southern populations. A secondary aim to test for similar geographical patterns in otolith-inferred metabolic rates, which reflect the energetic costs of standard metabolic rate (SMR) and other processes such as feeding, locomotion, thermoregulation, reproduction and growth, demonstrated a significant, positive relationship between otolith-inferred metabolic rate and latitude, which may reflect an increase in one or a combination of those physiological processes. The similar latitudinal pattern in growth and otolith-inferred metabolic rates is suggestive of greater intake of food per unit of time by northern fish. The phenotypic variation in physiological traits observed here demonstrates the significant adaptability of Arctic charr to different thermal regimes with different growing season lengths.

- On-going thermal studies using individual measurements of annual, or within-season growth determined from tag-recaptured Arctic charr were examined in relation to summer sea surface temperatures and within-season capture timing in the Ungava and Labrador regions of eastern Canada. Differences between two years of growth (2010-2011) were significant for Ungava Bay Arctic charr, with growth being higher in the warmer year. Growth of Labrador Arctic charr did not vary significantly among years (1982-1985). Regional comparisons demonstrated that Ungava Arctic charr had significantly higher annual growth rates, and experienced warmer temperatures than Labrador Arctic charr. The higher annual growth of Ungava Bay Arctic charr was attributed to the high sea surface temperatures experienced in 2010-11 and the localized differences in nearshore productivity as compared to Labrador. Within-season growth rates of Labrador Arctic charr peaked in June, declined toward August, and were negatively correlated with the length of time spent at sea and mean experienced sea surface temperatures. A quadratic model relating growth rate to temperature best explained the pattern of within-season growth. Collectively, results suggest that increases in water temperature may have profound consequences for Arctic charr growth in the Canadian sub-Arctic, depending on the responses of local marine productivity to those same temperature increases.
- As part of continuing tool development to better understand the responses of Arctic charr to the varying environments in which they live, MH genetic methods were used to show that using the β subunit of the Major Histocompatibility (MH) genes as a population marker it was possible to differentiate Arctic charr lineages previously defined using mDNA and to isolate all the populations studied within those lineages. The majority of the variation observed among Artcic charr was determined to have occurred prior to the last glaciation event. Despite this, Arctic charr populations were differentiated using both MH Class II β sequences and allelic frequencies. Thus the MH tool should allow differentiation of Arctic charr populations that were not previously genetically distinguishable, which will facilitate understanding the importance of genotype in differentiation of sympatric morphotypes.
- For centuries, and still today, fishing and hunting of local natural resources have been a source of food and a part of the culture of the Inuvialuit of the Western Arctic region. Climate change is affecting northern species on which the Inuvialuit rely for food including their fish resources.
- Local expert Traditional Knowledge of the environment shows the air temperatures are warming, the ocean water is warming, the sea ice is thinner, the winds are stronger and there are more rain and storm events.
- The warmer temperatures are affecting lake ice resulting in earlier break up and later freeze up and thus potentially longer growing seasons for the char. Sea-ice thickness is also changing in the regions surrounding Sachs Harbour.

- Studying Arctic Char, Arctic freshwater ecosystems and the local environment using both scientific and local expert Traditional Knowledge has produced a more robust suite of monitoring indicators that incorporate local expertise and understanding of the resource.
- The importance of char as a subsistence food to Inuvialuit Settlement Region communities requires on-going and effective community-based monitoring plans (CBMPs) that ensure continual local observation and monitoring to contribute towards effective proactive management of this valuable resource in light of the effects of climate variability and change.

OBJECTIVES

Five key objectives laid out for the 2014-15 extension work included:

1. the continued construction of long-term time series data on Arctic charr migration and growth in the Ungava Bay area;
2. the completion of supplementary sampling for the analysis of Beaufort Sea foodwebs;
3. the use of mercury analysis methods to document temporal changes in lacustrine foodwebs in lakes used for recreational fishing proximate to Kuujjuaq;
4. continuation and expansion of initiatives begun in the western Arctic to document THg in Dolly Varden Charr and Arctic charr marine tagging initiatives in the eastern Arctic; and
5. study of new ways of monitoring local Arctic charr populations using the resources and knowledge of scientists and local residents to create effective, long-term, community-based monitoring programs.

For Objective 1, a key sub-objective to be assessed included:

- Continuation of the PIT-tag monitoring series designed to assess the importance of marine temperatures for growth in Arctic charr and potentially competing anadromous whitefish and trout species (*Coregonus clupeaformis and Salvelinus fontinalis*) with collected data to be used to test facilitate improved understanding of shifts in competition between fish species that may negatively impact Arctic charr as climates warm.

For Objective 2, a key sub-objective to be assessed included:

- Completion of supplementary sampling in the Beaufort Sea and completion stable isotope analysis of collected samples for improved description of Beaufort Sea deep-sea foodwebs, with additional sampling facilitating better description of Beaufort shelf and slope foodwebs at depths >1500 m and permitting first time description of profundal Arctic marine food webs that support both marine and anadromous fish production.

For Objective 3, a key sub-objective to be assessed included:

- Documentation of temporal changes in total mercury (THg) concentrations in key fish species in lakes used for recreational fishing proximate to Kuujjuaq, notably Stewart Lake, with current data to be compared to baseline studies completed in Stewart Lake in 1999 to determine temporal changes in relation to increasing local development and climate change. The study will aid in improving scientific understanding of THg in local lakes used for recreational fishing and given the limited local supply of fish and the reliance of Kuujjuaq on subsistence harvests from Stewart Lake, thereby facilitating better understanding of the human health risks associated with local fish consumption.

For Objective 4, a key sub-objective to be assessed included:

- Expansion of initiatives begun in the western Arctic to document THg in Dolly Varden charr and Arctic charr marine tagging initiatives in the eastern Arctic aims to improve temporal sampling data base for Dolly Varden charr to refine existing temporal trend analyses and expansion of Arctic charr marine tagging initiatives with the use of marine telemetry studies aims to document and better understand thermal habitat use by anadromous Arctic charr. Planned acoustic telemetry work will specifically aim to [a] improve understanding of the marine environment habitat use by Arctic charr, and, [b] improve understanding of over-wintering freshwater environment habitat use.

For Objective 5, key sub-objectives to be assessed included:

- Use a collaborative and interdisciplinary approach to determine effective environmental and biological indicators which can be used by Inuvialuit Settlement Region (ISR) communities to monitor Arctic Char in a changing environment.
- Conduct new and innovative research which includes IK and social research methods linked to scientific studies on important Arctic resources.
- Examine IK-derived environmental indicators of change in growth for Arctic Char identified through IK interviews with local expert.
- Examine meteorological and hydrological data for the areas surrounding the study sites to determine effects on Arctic Char growth.
- Characterize lake habitat conditions and compare between study lakes to determine effects on Arctic Char growth.
- Examine potential relationships between annual environmental conditions (using IK indicators) and annual growth rates of Arctic Char.
- Identify effective indicators for community monitoring and fisheries management purposes with community input.
- Use IK and local expertise to implement effective CMBPs for char in ISR communities.

INTRODUCTION

The Charr Project as originally configured had several key research aims that focused on: [1] building research collaborations with Nunavik Research to improve understanding of Arctic charr in the marine environment and the possible impacts of climate change on the Arctic charr fishery; [2] reduce the known data deficiencies concerning mercury contamination levels in Dolly Varden charr that are of significant cultural and dietary importance for the Inuvialuit and Gwich'in; [3] collaborate with on-going sampling initiatives in the Beaufort Sea to address critical questions with respect to the function and structure of Beaufort Sea foodwebs as they pertain to anadromous fish species; [4] continue development of collaborative opportunities to improve the overall ecological, genetic and contaminant understanding of critical northern Arctic charr resources; and to [5] examine the effects of climate change on an Arctic Charr subsistence resource in the Inuvialuit Settlement Region and support the development of long term community based monitoring of the resource in one community in this region. In the context of the 4th year project extension, these objectives were expanded on and modified to meet a specific set of sub-objectives that could be successfully completed within a limited time and with a single year of funding. Objectives as defined for the extension year drew specifically on the knowledge gaps identified by previous ArcticNet work so as to ensure a continuum of effort and knowledge accumulation. For example, we have identified knowledge gaps in our understanding of the environments used by anadromous charr and in our temporal view of the impact of changing or variable environments on Arctic charr. Specific knowledge gaps include a lack of understanding of the marine foodwebs within which charr forage and grow and long-term implications change, which requires long-term data sets suitable for quantifying the impacts of change. As noted by Allard and Lemay (2012), "...there is value in long-term fisheries data and the extension of programs in the North to acquire matching fishery and environmental data. This should be encouraged to facilitate better understanding of long term environmental change, including climate, on Arctic charr and other key northern fishery resources." Accordingly, work planned and completed for the 2014-15 project year emphasized studies that addressed identified knowledge gaps (as noted above). These included: [1] the continued construction of long-term time series data on Arctic charr migration and growth in the Ungava Bay area, [2] the completion of supplementary sampling for the analysis of Beaufort Sea foodwebs, [3] the use of mercury analysis methods to document temporal changes in lacustrine foodwebs in lakes used for recreational fishing proximate to Kuujjuaq, and [4] the continuation and expansion of initiatives begun in the western Arctic to document THg in Dolly Varden charr and Arctic charr marine tagging initiatives in the eastern Arctic.

Further, this was the last year of Component 5 of the research. There was a heavy focus on the community-based monitoring aspect of this component of the project as well as final analysis for manuscripts including a paper on the topic of community-based monitoring of charr in the Canadian Arctic.

The purpose of this sub-component research was to work with the community of Sachs Harbour to identify the best possible practices to design a successful Arctic Char community-based monitoring program, accomplished by examining all available data and knowledge to provide a novel and thorough understanding of steps for success. In this final year, the project was transferred to the community of Sachs Harbour for implementation in collaboration with the Inuvialuit Settlement Region–Community-Based Monitoring Program (ISR-CBMP). The purpose of this final year was to ensure the community was ready to take over the Arctic Char community-based monitoring plan designed through this research.

ACTIVITIES

Completed 2014 Research Activities:

[1]

<u>What</u>: Finalization and proofs correction of the following papers for final release in 2014 and finalization of joint collaborative reports and papers summarizing work research work related to previous cycle of ArcticNet funding as listed below:

1. Dixon, H. J., Dempson, J. B. and Power, M. 2015. Assessing the use of different marine growth zones of adult Atlantic salmon scales for studying marine trophic ecology with stable isotope analysis. Fisheries Research. 164:112-119.
2. Conejeros, P. Phan, A., Power, M., O'Connell, M., Alekseyev, S., Salinas, I. and Dixon, B. 2014. Differentiation of sympatric Arctic charr morphotypes using Major Histocompatibility Class II genes. Transactions of the American Fisheries Society. 143:586-594.
3. Murdoch, A., Dempson, J. B., Martin, F. and Power, M. Temperature-growth patterns of individually tagged anadromous Arctic charr *Salvelinus alpinus* in Ungava and Labrador, Canada. Submitted to Ecology of Freshwater Fish. Article first published online: 9 APR 2014. DOI: 10.1111/eff.12133.
4. Sinnatamby, R. N., Dempson, J. B., Reist, J. D. and Power, M. 2014. Latitudinal variation in growth and otolith-inferred field metabolic rates of Canadian young-of-the-year Arctic charr. Ecology of Freshwater Fish. Article first published online: 19 JUL 2014, DOI: 10.1111/eff.12166.

5. Tran, L. Reist, J. D. and Power M. 2014. Total mercury concentrations in anadromous Northern Dolly Varden from the northwestern Canadian Arctic: A historical baseline study. Submitted to Science of the Total Environment. Available on-line June 2, 2014. DOI: 10.1016/j.scitotenv.2014.04.099.
6. Chételat, J. Amyot, M., Arp, P., Blais, J., Depew, D., van der Velden, S., Emmerton, C., Evans, M., Gamberg, M., Gantner, N., Girard, C., Graydon, J., Kirk, J., Lean, D., Lehnherr, I., Muir, D., Nasr, M., Poulain, A., Power, M., Rencz, A., Roach, P., Stern, G. and Swanson, H. Mercury in freshwater ecosystems of the Canadian Arctic: Recent advances on its cycling and fate. Submitted to Science of the Total Environment. Available on-line June 30, 2014. DOI: 10.1016/j.scitotenv.2014.05.151.
7. van der Velden, S., Dempson, J. B. and Power, M. 2014. Comparing mercury concentrations across a thirty year time span in anadromous and non-anadromous Arctic charr from Labrador, Canada. Science of the Total Environment. Available on-line December 27, 2013. DOI: 10.1016/j.scitotenv.2013.11.147.
8. Swanson, H. K., Lysy, M., Power, M., Stasko, A. D., Johnson, J. D. and Reist, J. D. 2014. A new probabilistic method for quantifying n-dimensional ecological niches and niche overlap Ecology. Pre-print doi: http://dx.doi.org/10.1890/14-0235.1.

Where: All work completed in laboratory settings at the University of Waterloo (manuscript writing, revision and proofing) or in government laboratories (collaborative writing of the Chételat et al. 2014).

When: van der Velden ,Murdoch, Tran, Dixon, Sinnatamby et al. manuscripts: analysis completed January 2013 through March 2014, final proofing completed April through December 2014. Chételat et al. report and manuscripts: revision and proofing completed January through March 2014. Conejeros et al. manuscript revision and proofing completed January through September 2014. Swanson et al. manuscript revision and proofing completed January through December 2014.

Who: MSc students van der Velden, A. Murdoch, L. Tran, PhD students Dixon and Sinnatamby, Dr. M. Power and co-authors P. Conejeros, J. B. Dempson, B. Dixon and others as listed above.

How: Face-to-face collaboration and discussion of written material.

[2]

What: Finalization and submission of: Tran, L., Reist, J. D. and Power, M. Life-history dependent variation of total mercury concentrations in Northern Dolly Varden from the Babbage River, Yukon Territory, Canada. Submitted to Science of the Total Environment. A study linking differences in THg in Dolly Varden charr to life-history tactics and indicated that for a given size, anadromous Dolly Varden charr contained more THg than riverine Dolly Varden charr because of differences in the baseline THg of occupied habitats. Acquisition of further samples for analysis based on 2014 field sampling. Work completed here relates to objective 4 of the extended project.

Where: All work completed in 2014, completed in laboratory settings at the University of Waterloo (statistical analysis, manuscript writing, proofing for submission).

When: Analysis completed January 2014 through November 2014.

Who: MSc student L. Tran, collaborator J. D. Reist and supervisor Dr. M. Power.

How: Face-to-face collaboration and discussion of written material.

[3]

What: Completion of field sampling on Stewart Lake where the entire fish community and interpretative baseline samples were obtained for total mercury (THg) and stable isotope analyses. Sampling designed to replicate earlier sampling completed in 1999, with the intent of comparing how known warming climates have impacted the recreational fish resources of the town of Kujjuaq. Work here relates to objective 3 of the extended project.

Where: All sampling work completed in Stewart Lake. Samples processed in Kujjuaq, stable isotope and THg analyses currently on-going in University of Waterloo laboratories.

When: Filed work and sampling completed July-August in Stewart Lake and Kuujjuaq. Laboratory analysis on-going September 2014 to June 2015.

Who: Nunavik Research Biologist L. Tran, U of W laboratory technicians and Dr. M. Power.

How: Via gill-netting, electro-fishing and use of sophisticated modern laboratory analytical devises.

[4]

What: Atlantic salmon scale methods paper. The use of fish scales in stable isotope ecology studies is becoming increasingly prevalent, especially for rare species where non-lethal sampling methods are preferable. This study assesses the use of different scale sections to test different hypotheses.

Where: Sampling off the West Greenland coast in conjunction with the SALSEA Greenland initiative. All work completed in laboratory settings at the University of Waterloo (statistical analysis, manuscript writing, proofing for submission).

When: All field and lab work completed by the end of April 2013. Paper submitted to Fisheries Research September 2013, and accepted with revisions October 2014.

Who: M. Power, J. B. Dempson, T. F. Sheehan, M. D. Renkawitz, K. Mitchell (BSc laboratory technician), H. Dixon (PhD student).

How: Samples obtained via gillnetting by local fishers at three communities along the West Greenland coast. All stable isotope analysis completed at the University of Waterloo using a Delta Plus Continuous Flow Stable Isotope Ratio Mass Spectrometer (Thermo Finnigan, Bremen, Germany) coupled to a Carlo Erba elemental analyzer (Carbo-Erba, Milan, Italy). Analysis followed face-to-face collaboration and discussion of written material. Published as Dixon, H. J., Dempson, J. B. and Power, M. 2015. Assessing the use of different marine growth zones of adult Atlantic salmon scales for studying marine trophic ecology with stable isotope analysis. Fisheries Research, 164: 112–119.

[5]

What: Atlantic salmon dietary analysis paper using gut content analysis and stable isotope analysis. This study assesses Atlantic salmon diet in the Northwest Atlantic, something which has not been done since the late 1960s.

Where: Sampling off the West Greenland coast in conjunction with the SALSEA Greenland initiative. All work completed in laboratory settings at the University of Waterloo (statistical analysis, manuscript writing, proofing for submission).

When: All lab and field work done by March 2014. All analysis done by August 2014. Paper submitted to ICES Journal of Marine Science in January 2015.

Who: M. Power, J. B. Dempson, T. F. Sheehan, M. D. Renkawitz, K. Mitchell (BSc laboratory technician), H. Dixon (PhD student).

How: Samples obtained via gillnetting by local fishers at three communities along the West Greenland coast. 10% gut contents analysis completed at the University of Waterloo, while the remaining 90% was completed under supervised contract by Normandeau Associates, Inc., (Falmouth, MA. USA). All stable isotope analysis completed at the University of Waterloo using a Delta Plus Continuous Flow Stable Isotope Ratio Mass Spectrometer (Thermo Finnigan, Bremen, Germany) coupled to a Carlo Erba elemental analyzer (Carbo-Erba, Milan, Italy). Analysis followed face-to-face collaboration and discussion of written material. Results disseminated at the ArcticNet 9th Annual Scientific Meeting, Dec 9-13, 2013, Halifax, NS, Canada, via a presentation (Dixon, H. J., Dempson, J. B., Sheehan, T. F., Renkawitz, M. D. and Power, M. Assessing trophic ecology of migrating Atlantic salmon (*Salmo salar L.*) caught off the West Greenland coast); and the NoWPaS Workshop, Apr 8-11, 2014, Värmland, Sweden via a presentation (Dixon, H. J., Dempson, J. B., Sheehan, T. F., Renkawitz, M. D. and Power, M. Spatial and temporal differences in Atlantic salmon marine feeding in the Northwest Atlantic). Submitted as Dixon, H. J., Dempson, J. B., Sheehan, T. F., Renkawitz, M. D. and Power, M. 2015. Assessing the diet of Atlantic salmon (*Salmo salar L.*) off the West Greenland coast using gut content and stable isotope analyses. ICES Journal of Marine Science.

[6]

What: Atlantic salmon trophic ecology investigation using stable isotope metrics to investigate differences in salmon diet, niche width and niche overlap with latitude and across small spatial scales. This paper will examine diet differences and the potential for terrestrial-marine coupling with the Greenland fjord ecosystem.

Where: Sampling off the West Greenland coast in conjunction with the SALSEA Greenland initiative. All work completed in laboratory settings at the University of Waterloo (statistical analysis, manuscript writing, proofing for submission).

When: Completion of lab work in April 2014. Completion of analysis January 2015. Paper ready for submission by April 2015.

Who: M. Power, J. B. Dempson, T. F. Sheehan, M. D. Renkawitz, K. Mitchell (BSc laboratory technician), H. Dixon (PhD student).

How: Samples obtained via gillnetting by local fishers at three communities along the West Greenland coast. All stable isotope analysis completed at the University of Waterloo using a Delta Plus Continuous Flow Stable Isotope Ratio Mass Spectrometer (Thermo Finnigan, Bremen, Germany) coupled to a Carlo Erba elemental analyzer (Carbo-Erba, Milan, Italy). Analysis followed by face-to-face collaboration and discussion of written material. Results disseminated at Arctic Change, the ArcticNet 10th Annual Scientific Meeting, Dec 8-12, 2014, Ottawa, ON, Canada, via a presentation (Dixon, H. J., Dempson, J. B. and Power, M. Characterising differences in the trophic ecology of North American Atlantic salmon (*Salmo salar L.*) along the West Greenland coast using stable isotopes).

[7]

What: Continued monitoring of Nepihjee River Arctic charr population. PIT-tagging 228 Arctic charr and 15 fish from competitor species. A total of 13 recaptures from previous years were recorded. Work completed here relates to objective 1 of the extended project.

Where: Field site on the Nepihjee River.

When: August to September 2014.

Who: Nunavik Research fisheries technicians, L Tran and A Storm-Suke, U of Waterloo.

How: Via live capture of Arctic char in a special purpose live trap inserted into a fishway and use of standard PIT-tagging equipment.

[8]

What: Continued tagging and monitoring of acoustic tagged Arctic charr in the marine environment for purposes of monitoring marine thermal habitat use, determining over-wintering behaviour in lakes, measuring climate change responses along a latitudinal gradient and monitoring of competitive interactions with other salmonids. Work completed here relates to objective 4 of the extended project.

Where: Field site at Pistolet Bay, Newfoundland (n=20 fish tagged) and Gilbert Bay, Labrador (n=40 fish tagged).

When: May to August 2014.

Who: Corey Morris and Curtis Pennell, DFO, Dr M. Power, University of Waterloo.

How: Recording of fish movement and temperature use in Arctic char with Vemco V13 acoustic tags. Monitoring and recording of fish location and temperature using a special purpose array of receivers in both marine and freshwater environments.

[9]

What: Completion of MSc thesis focused on mercury in Dolly Varden charr (Variations in Northern Dolly Varden (*Salvelinus malma malma*) total mercury concentrations from the northwestern Canadian Arctic) by L. Tran.

Where: Laboratories at the University of Waterloo.

When: January to November 2014.

Who: MSc student L. Tran.

How: Sample analysis for THg completed via thermal decomposition and atomic absorption spectroscopy following U.S. EPA method 7473 (U.S. Environmental Protection Agency 2007) using a Milestone Direct Mercury Analyzer (DMA-80) at the University of Waterloo. Sample analysis for stable isotopes completed via tissue excising of archive fillets in DFO facilities in Winnipeg and mass spectrometry analysis at the Environmental Isotope Laboratory at the University of Waterloo using a A Delta Plus Continuous Flow Stable Isotope Ratio Mass Spectrometer (Thermo Finnigan, Bremen, Germany) coupled to a Carlo Erba elemental analyzer (Carbo-Erba, Milan, Italy). Completion of statistical analysis and writing, with review comments provided by J. D. Reist, DFO.

[10]

What: Stable isotope analysis from samples collected during the second (2013) field season. Samples were collected and analysed to determine the food web structure of the slope and shelf areas of the Beaufort Sea, with emphasis on the fish component of the food web.

Where: Tissue processing and all stable isotope analyses conducted at the University of Waterloo. Tissue extraction from organisms that have been shared with other collaborators conducted at the University of Manitoba and the Fisheries and Oceans Freshwater Institute, Winnipeg, MB.

When: Completion of tissue processing for analysis by April 2014. Near completion of stable isotope analysis as of February 2015 (about 500 samples left to be analysed). Tissue processing of samples from the third (2014) field season commenced in November, 2014, but stable isotope analysis is on hold until all data from the previous field seasons are received. Samples from 2014 will mainly be used to fill in data gaps.

Who: M. Power, J. Reist, Ashley Stasko (PhD student), Andrea Storm (laboratory technician, UW), Adrienne Smith (laboratory technician, UW), Amanda Conway (laboratory technician, UW), and Kurtis Ulrich (BSc laboratory technician, DFO).

How: Tissue extraction was conducted by Ashley Stasko (PhD student) in a University of Manitoba laboratory in conjunction with technicians at the Fisheries and Oceans Canada Freshwater Institute, Winnipeg. Extracted tissues were sent to the

University of Waterloo, where they were processed (dehydrated and ground). Stable isotope analysis was completed using a Delta Plus Continuous Flow Stable Isotope Ratio Mass Spectrometer (Thermo Finnigan, Bremen, Germany) coupled to a Carlo Erba elemental analyzer (Carbo-Erba, Milan, Italy).

[11]

What: Finalization and submission of: Girlado, C., Stasko, A., Choy, E.S., Rosenburg, B., Majewski, A., Power, M., Swanson, H., Loseto, L., and Reist, J.D. Trophic variability of Arctic fishes in the Canadian Beaufort Sea: a fatty acids and stable isotope approach. Submitted in January 2015 to Polar Biology. Fatty acid and stable isotope analyses were used to study the trophic ecology of the 10 most abundant benthic fish species sampled in the Beaufort Sea in 2012 and 2013. Analyses revealed trophic separation between agonids (alligatorfish) and cottids (sculpins), but suggested substantial trophic overlap among several species of zoarcids (eelpouts). A strong contribution of pelagic carbon was detected in most benthic fishes. This is one of the first in-depth analyses of trophic overlap among these Arctic fishes, and will help to fill in large knowledge gaps in specific feeding ecology of benthic Arctic fishes.

Where: Analysis and writing for the stable isotope component was conducted at the University of Waterloo while writing and analysis for the fatty acid component was conducted at the University of Manitoba.

When: Laboratory analysis, statistical analysis and manuscript preparation from May, 2014 to January, 2015.

Who: Collaborator C. Giraldo, PhD Student A. Stasko, PhD Student E. Choy, collaborator B. Rosenburg, collaborator A. Majewski, supervisor M. Power, supervisor H. Swanson, collaborator L. Loseto, and collaborator J. Reist.

How: Face-to-face, phone, and email discussion of statistical analysis and written material. Results were also disseminated at the Arctic Change Conference, 8-12 December, 2014, in Ottawa, ON, Canada via a poster (Girlado, C., Stasko, A., Choy, E.S., Rosenburg, B., Majewski, A., Power, M., Swanson, H., Loseto, L., and Reist, J.D. Trophic patterns of Arctic fishes in the Canadian Beaufort Sea: A fatty acid and stable isotopes approach).

[12]

What: Ongoing analysis and preparation of manuscript quantifying size structure (body size vs. abundance and body size vs. trophic level) in benthic food webs from the shelf and slope habitats of the Beaufort Sea, with an emphasis on the fish community. Preliminary results suggest smaller predator-to-prey mass ratios, longer food chains, and steeper scaling between abundance and body size in the Beaufort Sea than those quantified for North Sea fish communities, suggesting there is less energy available to larger size classes. Preliminary results also identified a subset of fish that are decoupled from the energy pathways structuring the remainder of the benthic fish community. Changes in size structure can be useful for tracking human and climate-related changes in Arctic marine food web structure. This study will provide quantitative indices of trophic structure against which future studies can compare values for evidence of change. Size-structured indices, in conjunction with trophic information gained from stable isotopes, will also provide insight about energy transfer efficiency and resilience in both deep-sea and shallow shelf Beaufort food webs. The manuscript will be a result of the first chapter in Ashley Stasko.s PhD thesis.

Where: Analysis and writing conducted at the University of Waterloo.

When: Analysis commenced in November, 2014. Expected submission in May, 2015.

Who: PhD Student A. Stasko, supervisor M. Power, supervisor H. Swanson, collaborator A. Majewski, collaborator S. Atchison, collaborator L. de Montety, collaborator P. Archaumbault, and collaborator J. Reist.

How: Face-to-face, phone, and email discussion of statistical analysis and written material. Preliminary results were disseminated at the Arctic Change Conference, 8-12 December, 2014, in Ottawa, ON, Canada via a poster (A. Stasko, M. Power, H. Swanson, L. de Montety, P. Archaumbault, A. Majewski, S. Atchison, and J. Reist. Evidence for size-structured marine food webs in the Beaufort Sea: Comparison between dynamic shelf and stable mesobenthic habitats).

[13]

What: Completion of third (2014) field season. Samples were collected to determine the food web structure of the slope and shelf areas of the Beaufort Sea, with emphasis on the fish component of the food web.

Where: Beaufort Sea in conjunction with the Beaufort Regional Environmental Assessment initiative (BREA).

When: Third field season was conducted August-September of 2014 during the F/V *Frosti* summer sampling program.

Who: Ashley Stasko (PhD student) joined the sampling crew on the F/V *Frosti*.

How: Samples were obtained via various trawling nets and a box core sampler aboard the ship F/V Frosti. Frozen samples were shipped to the Fisheries and Oceans Canada Freshwater Institute, where tissues could be extracted and shared among collaborators.

[14]

What: Continued characterization of the variation in immunological responsiveness of Arctic charr across northern Canada and the development tools for improved genetic differentiation among populations and/or improved prediction of physiological impacts of climate change on Arctic charr. Work here rleates to objective 4 of the extended project.

Where: University of Waterloo laboratories.

When: January to December 2014 and on-going.

Who: PhD student T. Robinson, B. Dixon, R. and M. Power.

How: Using state-of-the-art genotyping methods (MH) as described in the methods of DNA extraction and genotyping described by Conjeros et al. (2008, 2013). Results partially disseminated at the ArcticNet 10th Annual Scientific Meeting: Arctic Change 2014, December 8-12, Ottawa, Ontario via a poster: Robinson, T., Conjeros, P., Power, M. and Dixon, B. 2014. Polymorphism of major histocompatibility class i classical and non-classical genes in Arctic charr (*Salvelinus alpinus*).

[15]

What: Presentation of interim results to appropriate national and international conferences. Work here relates to objectives related to all components of the project.

Where: 5th Annual International Otolith Symposium, Palma de Mallorca, Spain; Canadian Conference for Fisheries Research, Yellowknife; and, ArcticNet 10th Annual Scientific Meeting: Arctic Change 2014, December 8-12, Ottawa, Ontario.

When: January 2014, October 2014, and December 2014.

Who: M. Power, J.D. Reist, H. K. Swanson , T. Robinson, A Stasko, L. Tran , H.Dixon and numerous others.

How: Platform and poster presentations as follows:

1. Swanson, H., Tonn, W., Johnston, J., Loseto, L., Power, M., and Reist, J. 2014. Trophic ecology of coastal of fishes from Phillips Bay, Yukon Territory. 67th Canadian Conference for Fisheries Research. January 3-5, 2014. Yellowknife, Northwest Territories.
2. Tran, L., Reist, J. and Power, M. 2014. Life-history differences in Dolly Varden charr (*Salvelinus malma*) mercury concentrations. 67th Canadian Conference for Fisheries Research. January 3-5, 2014. Yellowknife, Northwest Territories.
3. Minke-Martin, V., Dempson, J. B., Sheehan, T. F. and Power, M. 2014. Otolith-derived estimates of marine temperature use by West Greenland Atlantic salmon (*Salmo salar*). 5th Annual International Otolith Symposium. October 20th-24th 2014. Palma de Mallorca, Spain.
4. Stasko, A., Power, Swanson, H., Archambault, P., de Montety, L., Majewski, A., Atchison, S. and Reist, J. 2014. Evidence for size-structured marine food webs in the Beaufort Sea: comparison between dynamic shelf and stable mesopelagic benthic habitats. ArcticNet 10th Annual Scientific Meeting: Arctic Change 2014, December 8-12, Ottawa, Ontario.
5. Tran, L., Reist, J. and Power, M. 2014. Life-history differences in Northern Dolly Varden (*Salvelinus malma malma*) total mercury concentrations. ArcticNet 10th Annual Scientific Meeting: Arctic Change 2014, December 8-12, Ottawa, Ontario.
6. Tran, L., Ford, B., Storm-Suke, A. and Power, M. 2014. Climate-induced changes in relative fish abundance and condition: implications for foodwebs and mercury tissue concentrations in the Stewart Lake fish community. ArcticNet 10th Annual Scientific Meeting: Arctic Change 2014, December 8-12, Ottawa, Ontario.
7. Robinson, T., Conjeros, P., Power, M. and Dixon, B. 2014. Polymorphism of major histocompatibility class i classical and non-classical genes in Arctic charr (*Salvelinus alpinus*). ArcticNet 10th Annual Scientific Meeting: Arctic Change 2014, December 8-12, Ottawa, Ontario.
8. Dixon, H., Dempson, J. B. and Power, M. 2014. Characterising differences in the trophic ecology of North American Atlantic salmon (*Salmo salar l.*) along the West Greenland coast using stable isotopes. ArcticNet 10th Annual Scientific Meeting: Arctic Change 2014, December 8-12, Ottawa, Ontario.
9. Giraldo, C., Choy, E., Stasko, A., Rosenberg, B., Power, M., Swanson, H., Loseto, L. and and Reist, J. D. 2014. Trophic patterns of Arctic fishes in the Canadian Beaufort Sea: a fatty acid and stable isotopes approach. ArcticNet 10th Annual Scientific Meeting: Arctic Change 2014, December 8-12, Ottawa, Ontario.

[16]

What: Completion of Arctic Char community-based monitoring analyses.

Where: Inuvik, NT.

When: April 2011 – October 2014.

Who: PhD Candidate J.Knopp.

How: Semi-directed interviews with Arctic Charr CBM experts working with communities in the Inuvialuit Settlement Region, Nunavut, Nunavik, and Nunatsiavut (Figure 1). Six Arctic Char CBMPs across the four Inuit regions were reviewed, including interviews and written questionnaires with a total of 12 Arctic Char community-based monitoring experts.

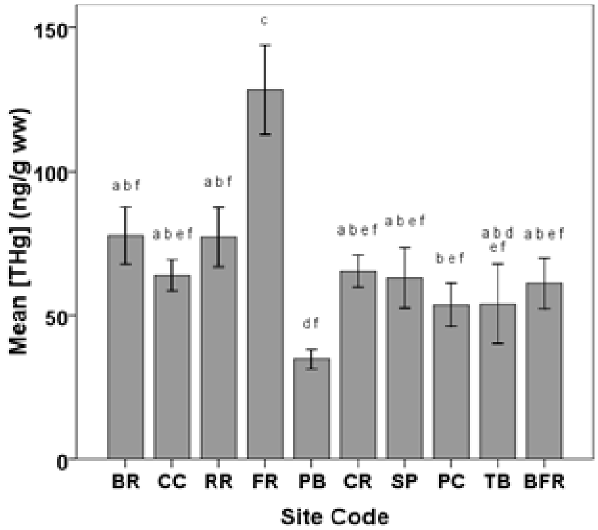

Figure 1. Mean length-adjusted [THg] (ng/g ww) for sampled sites. I-bars represent 95% confidence intervals. Sites with the same letter were not significantly different from one another (Tukey's HSD; p > 0.05). Sites: Babbage River, BR (30, 68°37'47"N, 139°22'12"W) sampled 1991; Cache Creek, CC (30, 68°31'11"N, 136°13'47"W) samples 1988; Rat River, RR, (67°46'48"N, 136°19'11"W) sampled 1988; Firth River, FR (68°40'12"N, 140°55'11"W) sampled 1988; Ptarmigan Bay, PB, (69°29'11"N, 139°01'12"W) sampled 1988; Canoe River, CR, (68°46'11"N, 138°45'00"W) sampled 1988; Shingle Point, SP, (68°58'48"N, 137°31'12"W) sampled 1989; Pauline Cove, PC, (69°34'47"N, 138°52'12"W) sampled 1989; Thetis Bay, TB (69°32'59"N, 139°01'48"W) sampled 1989 and Big Fish River, BFR (68°27'N, 136°10.5'W, 1991). Figure from Tran et al. 2015. © 2014 Elsevier B.V. All rights reserved.

Literature searches using databases allowing retrieval of both grey and peer-reviewed papers on char CBM in the Canadian Arctic. Analysis of data and knowledge gathered for emergent themes using NVivo software.

[17]

What: Transfer of Arctic Char CBMP to community of Sachs Harbour with unassisted local monitor data collection.

Where: Sachs Harbour, NT.

When: July-September 2014.

Who: PhD Candidate J.Knopp, Trevor Lucas and Kyle Wolki (Sachs Harbour local monitors).

How: J.Knopp and Trevor Lucas trained Kyle Wolki to collect scientific samples. Local monitors then carried out the entire scientific sampling effort on their own. Samples were sent to J. Knopp in Inuvik for quality control and quality assurance (QA/QC) and to be sent out for lab analyses. The QA/QC phase of the sampling effort was requested by the Sachs Harbour Hunters and Trappers Committee to ensure the local monitors are ready to take on the scientific sampling on their own.

[18]

What: Poster Presentation.

Where: ArcticNet Arctic Change International Conference, Ottawa ON.

When: December 2015.

Who: PhD Candidate J.Knopp.

How: Poster session.

[19]

What: Invertebrate expert identification of Arctic Char stomach contents from 2014 samples.

Where: York University, Toronto ON.

When: February-March 2015.

Who: PhD candidates Ryan Scott and Chris Luszczek.

How: Invertebrates from Arctic Char stomach contents sample preparations, expert identification to lowest taxononmic level possible and total counts for each taxon.

[20]

What: Final community visit, Community meetings for review final results and reports.

Where: Sachs Harbour NT.

When: February-March 2015 (upcoming)

Who: PhD Candidate J.Knopp, Sachs Harbour Hunters and Trappers Committees, community harvesters.

How: Meetings with Hunters and Trappers Committees and community meetings, one-on-one meetings with community research participants.

[21]

What: PhD dissertation and defence completion.

Where: Trent University, Peterborough ON and Inuvik NT.

When: April 2014-August 2015.

Who: PhD Candidate J.Knopp.

How: Thesis writing and edits, defence preparation in paper-based format so chapters are ready to be sent out for peer-review.

RESULTS

Published scientific results in 2014 made significant contributions toward increased understanding of fish in Arctic ecosystems and how they were being impacted by changing climates and contaminants. Work by Murdoch and Power (2014) noted significant regional differences in Arctic charr growth with Ungava Arctic charr having significantly higher annual growth rates than Labrador Arctic charr. The higher annual growth of Ungava Bay Arctic charr was attributed to the higher sea surface temperatures experienced and localized differences in nearshore productivity as compared to Labrador. Within-season growth rates of Labrador Arctic charr were found to peak in June, decline in August, and were negatively correlated with the length of time spent at sea and mean experienced sea surface temperatures. Overall results suggested that increases in water temperature may have profound consequences for Arctic charr growth in the Canadian sub-Arctic, depending on the responses of local marine productivity to those same temperature increases. Sinnatamby et al. (2014) further commented on climate change impacts, noting that evidence for a countergradient variation in Arctic charr whereby northern populations demonstrated faster growth rates compared to southern populations, although the latter were typically larger for a given age than the former.

Evidence was found for similar latitudinal pattern in growth and otolith-inferred metabolic rates suggestive of greater intake of food per unit of time by northern fish. The phenotypic variation in physiological traits observed demonstrates the significant adaptability of Arctic charr to different thermal regimes with different growing season lengths. Thus determining the relative contributions of phenotypic plasticity and genetic variation to the observed latitudinal variation will be critical to predicting the responses of Arctic charr to climate change more accurately. To that end, work by Conejeros et al. (2014) showed the genetics of studied Arctic charr populations presented high rates of non-synonymous/synonymous substitutions and high levels of inter-population variation, that suggested MH Class II β genetic markers could be used to assess polymorphisms and specializations in Arctic charr in ways that may represent both divergence by genetic drift and by natural adaptation to the local environment. Thus, Major Histocompatibility genetic methods have good potential for improving our understanding of likely climate-related impacts on Arctic charr.

In the area of contaminants, work by van der Velden et al. (2014) showed that although climate had warmed significantly in Labrador (1.6°C to

2.9°C) between 1977-78 and 2007-09, there was no consistent evidence of cliamte-related increased in total mercury (THg) content of either anadromous or lacustrine Arctic charr. The lack of an overall trend in anadromous or non-anadromous Arctic charr THg despite warming temperatures that favour increased mercury methylation suggests that regional changes in climate-driven factors have had limited impacts on mercury exposure in Labrador freshwater or marine fish in the Labrador region. The work of van der Velden et al. (2013a,b, 2104) also contributed to improved understanding of the overall spatial and temporal trends of changes in Arctic fish mercury levels as reported in Chételat, et al. (20140, notably that no geographic patterns or regional hotspots were evident. Tran et al. (2014) extended study of THg in anadromous fish to include Dolly Varden charr for the first time. The study established a critical baseline for THg levels in Dolly Varden charr based on samples obtained in the late 1980s to show that length-adjusted THg concentrations did not vary consistently either by latitude or longitude, that among-population variation in THg was best explained by fork-length, with an overall model of length-adjusted THg concentrations being best explained by a combination of age, $\delta^{15}N$, and $\delta^{13}C$. Overall mean THg concentrations were below Health Canada's consumption guideline for commercial sale of fish (0.5 ppm wet weight).

Finally techniques papers by Dixon et al. (2015) and Swanson et al. (2014) developed the tools for applying stable isotope methods to the study of Arctic fish. Specifically, Dixon et al. (2015) established that the measured whole marine growth zone can be used as a proxy for average marine feeding, while the commonly used 2nd summer growth zone was found not to be representative of earlier marine feeding. Swanson et al. (2014) developed methods for the use of stable isotope data in combination with other physical environmental data to better describe the fundamental niche of Arctic fish.

The monitoring of the Nepihjee River (Dry Bay, Ungava) returning Arctic charr run was continued for a period of 27 days, with a significant number of fish

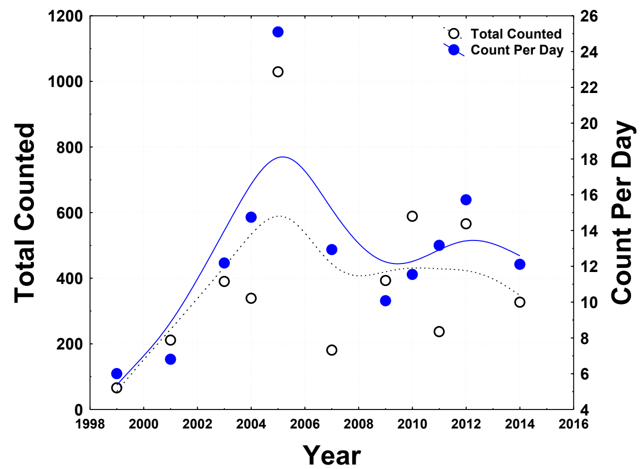

Figure 2. Numbers of returning Arctic charr counted at the Nephigee fishway 1999-2014 and average count per day. Lines plot the distance weighted least squares trends for the data. Mean number of fish counted per year = 393.5, standard deviation = 262.6.

being tagged (n=228) and a total of 327 fish counted ascending the fish way. The number was slightly below the long term average of 393.5 returning fish per year (Figure 2). Over the long-term (1999-2014) there has been a strong association between number of returns and days spent counting (r^2=0.56, P=0.008), with variation in number of days spent counting having been significantly influenced by the prevalence of high water or poor summer weather. Parallel monitoring and tagging of other species was begun in 2014 with a number of brook trout (n=2), round whitefish (n=14) and other miscellaneous species, including a lone Atlantic salmon (*Salmo salar*) noted ascending the fishway. Diel patterns in fish movement were noted, with fish initially moving more during the morning period and then switching in late August to movement in the afternoon period. Obtained observational data continue to show persistent use of the fishway by returning Arctic charr, with anecdotal observation still indicating a similar size range of returning fish. Of the fish captured n=13 were identified as having been previously tagged.

Studies of mercury in Arctic fishes continued in 2014 with the successful completion of a graduate

MSc thesis on mercury in Northern Dolly varden charr (*Salvelinus malma malma*) and acquisition of further samples for analysis. Most notable was the successful publication of the first chapter of the thesis examining spatial variation in a series of archival tissue samples that served to form a useful historical baseline for the species in the Yukon and Northwest Territories (Tran, L. Reist, J. D. and Power M. 2014. Total mercury concentrations in anadromous Northern Dolly Varden from the northwestern Canadian Arctic: A historical baseline study. Science of the Total Environment.) Total mercury (THg) concentrations were measured for three co-occurring forms of Dolly Varden charr, including: isolates, residents, and anadromous individuals from the Babbage River, Yukon Territory, Canada. Differences in mean THg concentrations were found starting at 22 ng/g ww in isolate, increasing to 56 ng/g ww in resident, and 108 ng/g ww in anadromous fish. The pattern of mercury loading is markedly different than that observed in other migratory charr species where anadromous fish typically have lower levels of THg. After adjusting THg to a standardized age and length, significant differences remained among the life-history types, with anadromous Northern Dolly Varden having the lowest THg concentrations. Trophic position was the most important factor in explaining observed differences among the individuals regardless of life-history types, with growth rate also contributing to explaining the variation among individuals. The contrast of higher absolute, but lower age and size adjusted, THg levels in anadromous fish was explained by a combination of two counter-acting mechanisms, including: 1) a switch to feeding at higher trophic levels and the use of prey with higher THg levels in the marine environment that raises THg levels, and 2) somatic growth dilution that, with increasing growth efficiency, decreases THg as fish age and increase in size. Additional samples obtained for analysis were too few (n=15) to meaningfully contribute existing analyses and have been archived for future use.

Mercury studies were also carried out in Stewart Lake, Nunavik, using fish data collected with standardized effort and gear type in Stewart Lake from two discrete periods (1999 vs 2014), between which significant local increases in mean summer temperatures occurred, the effects of climate warming on the fish community (relative abundance) and fish condition were examined to draw inferences about: [1] whether warming has been associated with significant structural ecological change, and, [2] what the consequences of change may be for measured Hg concentrations in the dominant predatory fish species (Lake trout) (Figure 3). Stewart Lake (58°11’ N, 68°26’W) is a small (9.9 km), shallow (≤12 m), oligotrophic lake located immediately north-west of Kuujjuaq, Nunavik, in the Ungava Bay drainage basin. The lake is situated at the northern limit of the tree line within a climatic zone moderated by the influences of the Ungava Bay circulation and supports a simple biological community. Fish were sampled using multifilament experimental gillnets (10–60 mm mesh) set at varying depths in the littoral, limnetic and profundal zones of the lake. To avoid minimum size-selective biases associated with netting alone, supplementary samples were obtained by using trot lines, minnow traps (5 mm mesh) and electro-fishing in randomly

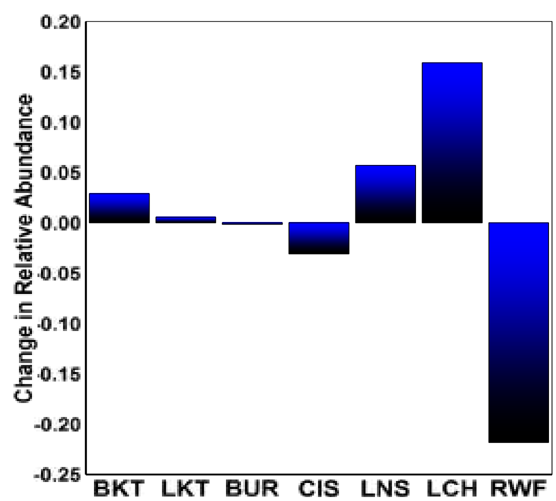

Figure 3. Changes in relative abundance of key fish species in Stewart Lake as inferred from common catch and gear methods 1999 versus 2014 using 1999 as the base. BKT=Brook trout, LKT=Lake trout, BUR=Burbot, CIS=Cisco, LNS=Longnose sucker, LCH=Lake chub, RWF=Round whitefish.

selected littoral habitats. Identical sampling methods, effort and gear were used in 1999 and 2014 to ensure data comparability. A sample of n=208 fish, comprising 9 species of fish were captured. Relative fish abundances shifted significantly in the period 1999-2014 (P2=43.54, P<0.001), with the change being driven by two species: Lake chub increased in relative abundance (Fisher's exact P<0.001) and Round whitefish declined (Fisher's exact p <0.001). Proportional catches of all other species showed no significant changes (P≥0.121). Brook trout which had previously been scarce in the lake were more abundant. Comparison of ^{13}C stable isotope values indicated that the two forage fish species showing the greatest changes in relative abundance had the greatest overlap in carbon resource use. Further stable isotope analysis is currently being completed on the samples and coupled total mercury analysis is being completed for all fish to test a series of hypothesis concerning the implications of the climate-driven changes in relative abundance on measured mercury concentrations in the apex predator, lake trout (*Salvelinus namaycush*).

Monitoring of 25 Arctic charr (mean length 46.5 cm ± 5.7 SD) tagged in 2013 at the entrance to Parkers Brook (Pistolet Bay, 51.5 N). A continued and over-wintering data collected in spring of 2014 with successful download of receivers placed in the over-wintering ponds. of the 25 fish tagged, 20 fish were detected having entered over-wintering ponds and they yielded 1.2 million detections throughout the winter months, particularly near the time of outmigration. The data collected form a useful analytical complement to data collected in 2012 at more northerly latitudes of Gilbert Bay (52.4 N). Unfortunately, extremely late and unusually heavy sea-ice conditions in spring 2014 prevented us from re-deploying hydrophones and further tagging of fish in the marine environment. However, hydrophones were successfully re-dpolyed in over-wintering ponds to increase winter habitat coverage during 2014/2015 and an additional 15 Arctic charr were tagged at Parkers Brook during 14-18 July 2014 upstream migration to over-wintering areas. The additional data will increase the sample size and facilitate meaningful statistical comparisons with over-wintering data collected previously at Gilbert Bay.

At Gilbert Bay a further n=20 Arctic charr were captured, tagged and monitored in the marine using an existing array of Vemco receivers deployed by DFO. For comparative purposes 20 Atlantic salmon were also tagged in a study coupled with the NSERC Ocean Tracking Network program.The DFO maintained network of 37 receivers that covers an area of some 330km^2 was used to track the tagged fish, with data downloads being completed in early October. Available data have not been analyzed, but have been sumarized and vetted for statistical analysis. It is also known that many of the tagged Arctic charr successully returned to over-wontering areas (Shinneys Pond) where the deployment of recievers for the over-winter period will provide a second year's worth of over-wintering movement data on Arctic charr. Coupled with the Pistolet Bay Arctic charr over-wintering data, this data will form the first comprehensive study of Arctic charr movement during the winter preiod collected anywhere in Canada, or elsehwere in the world.

Work continued with the development of tools for using Major Histocompatibility (MH) gene molecular techniques to better understand the evolutionary history of Arctic charr and its likely susceptibility to climate warming as a result of lack of immunological competency (i.e. increased susceptibility to disease). To that end, studies examining the potential for MH to differentiate among-populations at small spatial scales (i.e., within lakes) was published (Conejeros et al. 2014), with results showing that MH Class II β was an ideal marker to assess polymorphisms and specializations of Arctic charr as it represented both divergence by genetic drift and by natural adaptation to the local environment. Additional evaluation of the potential of classical MH genes to evaluate their potential as a population markers was completed. Results indicated that Arctic charr appear with two classical genes (UBA, UGA), genes responsible for initiating an immune response. Although both genes identify allelic lineages and can be sued to spearate populations, UGA provides better resolution based on geographic origin. Arctic charr has an exceptional ability to adapt to varied environments and the use of two classical genes, both UBA and UGA in the in the defense against local pathogens might be one mechanism that facilitates their adaptability. As a result of the success of this work, a large scale macro-analysis of variation among Canadian populations is currently being completed.

As part of a multi-agency initiative to better understand the ecosystem dynamics of the Beaufort Sea, significant progress has been made to complete the collection and analysis of samples to better characterise Beaufort Sea food web structure. The Canadian Beaufort Sea currently hosts 95 oil and gas leases, with recent exploration licenses issued for deep off-shelf waters. Climate-related changes in Arctic oceanography and sea ice are also occurring at unprecedented rates (IPCC 2007, Kwok and Rothrock 2009, AMAP 2012). A paucity of data regarding offshore food web structure, however, currently inhibits the ability to either document the impacts of climate and human-mediated change on offshore ecosystems or predict biological outcomes. In addition, there is little understanding of how offshore food webs may be linked to those in near-shore habitats which support a variety of estuarine and marine species utilized by northerners. In response, Fisheries and Oceans Canada, in association with a number of other government departments, undertook the Beaufort Regional Environmental Assessment (BREA) as a means of identifying significant gaps in the scientific and local stakeholder understanding of the Beaufort Sea ecosystem. One of the primary objectives of the BREA Marine Fishes Project was to characterise the structure and function of offshore marine food webs and their linkages to near-shore ecosystems. Gathered information will be used to provide sound scientific information for regional policy development, regulatory decisions, and project-specific environmental assessments.

In collaboration with DFO, we have now obtained some 4858 samples of offshore biota, of which 4386 have been chosen for stable isotope analysis. Biota were collected in 2012 and 2013 from station depths of 20 to 1500 m for both benthic and pelagic zones, respectively, along transects covering a wide geospatial range in the southern Beaufort Sea from the Alaskan border to the Amundsen Gulf. Sampling occurred from July to September 2012, July to September 2013, and again from August to September 2014 using zooplankton hauls, mid-water fishing trawls, and benthic trawls deployed from the F/V *Frosti*. Samples from all field seasons were catalogued by DFO and a subsample was shipped to the University of Waterloo for processing in the months following sampling (samples received between November of each sampling year to June of the following year). Processing and submission for stable isotope analysis was completed at the University of Waterloo for all received samples by February 2015, with a final 511 fish pending shipment from DFO. Samples chosen for stable isotope analysis are representative of a wide taxonomic range, with some 36 species of fish, 22 orders of invertebrates, and 17 orders of zooplankton from 2012 and 2013 combined, as well as some 70 sediment samples. Tissue samples from biota are linked to complementary occurrence, relative abundance, and diversity data as well as habitat descriptors (e.g., depth, substrate, temperature, salinity) available through the collection of standard oceanographic variables obtained coincident with biota sampling. A subset of fish samples also have complimentary fatty acid composition data, providing additional dietary information.

Towards the objective of characterising the offshore food web structure of the Beaufort Sea and its connection to nearshore food webs, we took part in the development of a new statistical method for quantifying ecological niche overlap (Swanson, H. K., Lysy, M., Power, M., Stasko, A. D., Johnson, J. D. and Reist, J. D. 2014, cited above in completed 2014 research activities under task 1). Although this method was not developed specifically for the Beaufort Sea data, its application to stable isotope data from the Beaufort Sea will become a key tool for analyses of dietary partitioning among biota. The stable isotope data obtained from the Beaufort Sea were further used directly in conjunction with fatty acid analyses to quantify trophic overlap between the most commonly sampled Arctic fish species in the BREA program. Results were described in a recently submitted paper (Giraldo et al. Trophic patterns of Arctic fishes in the Canadian Beaufort Sea: a fatty acid and stable isotopes approach) currently being reviewed by Polar Biology. Briefly, fatty acid (FA) and stable isotopes analyses (SIA) were used to study the trophic ecology of 10 of the most abundant benthic fish species in the Canadian Beaufort Sea. Both methods revealed among- and within-species variability in the foraging habitat and diet composition of these fishes. Correspondence analysis of FA signatures identified resource partitioning among agonids (*Aspidophoroides olrikii, Leptagonus decagonus*) and cottids (*Gymnocanthus tricuspis, Triglops pingelii*), and dietary overlap among zoarcids (*Lycodes frigidus, Lycodes seminudus*). Diatom- and *Calanus*-derived FA were present in all species suggesting a strong contribution of pelagic FA to benthic fish communities. Mean SI values also differed among-species and indicated a large range of trophic positions (max $\delta^{15}N$ range of 3.6 for *L. frigidus*) and carbon dietary sources are exploited by fishes (max $\delta^{13}C$ range of 2.9 for *T. pingelii*). Finally, among-species variability was greater than intra-specific variability validating the use of prey FA signatures in the dietary studies of top predators.

The stable isotope data obtained from the collaboration with BREA has facilitated a third analysis aimed at quantifying the size structure of demersal fish communities in the near-shore and offshore Beaufort Sea to test hypotheses regarding the effects of size on trophic structure and energetic transfer efficiency along the food chain. Marine food webs are often strongly size-structured, such that trophic level increases continuously with body mass regardless of species identity, and larger organisms are less abundant due to inefficient energetic transfer between trophic steps (Jennings and Mackison 2003). Within a size-structured community, it has been predicted that stable ecosystems will promote longer food chains with smaller predator-prey mass ratios (i.e., small size differences between organisms in successive trophic levels), resulting in lower energetic transfer efficiency between trophic steps and steeper negative slopes in abundance-body mass relationships. These theories have yet to be tested in an Arctic marine environment where resources at the bottom of the food web are limited, seasonal, and highly recycled. An analysis is currently underway that to test the hypotheses that (1) the size-structured hypothesis is applicable to demersal Arctic marine food webs in the Beaufort Sea (i.e., that body mass will have higher explanatory power for trophic level when individuals are grouped by size compared to when they are grouped by species identity), and (2) relatively stable benthic habitats in the mesobenthic zone (750 to 1000 m) have lower energy availability at larger size classes compared to dynamic shelf habitats (<50 m) that are annually disturbed by ice scouring. The study draws on isotopic and body size data from some 1461 fish comprising 24 species collected in 2012 and 2013 along five transects that spanned the continental Beaufort Shelf from depths of 20 to 1000 m. Preliminary results using data from the 2012 field season indicate that fish communities in the Beaufort Sea are generally size structured, with smaller predator-to-prey mass ratios, marginally longer food chains, and shallower size spectra slopes in stable, mesobenthic habitats. The study also revealed several species of eelpout (*Lycodes spp*.) that appear to be decoupled from the energetic pathways structuring the rest of the demersal fish community (Figure 4).

As part of a second multi-agency initiative to understand better the marine portion of the Atlantic salmon life cycle, samples were taken from Atlantic salmon caught off the West Greenland coast for a number of different investigations, including parasite load, diseases, lipid content and body condition, genotyping, stable isotope analysis and gut contents analysis. The marine portion of the Atlantic salmon life-cycle is poorly understood, and is the portion of the life-history where most mortality is taking place, despite a reduction in commercial fishing. The North Atlantic Conservation Organisation (NASCO), in association with a number of organisations from Greenland, the USA, Canada, the UK and Ireland,

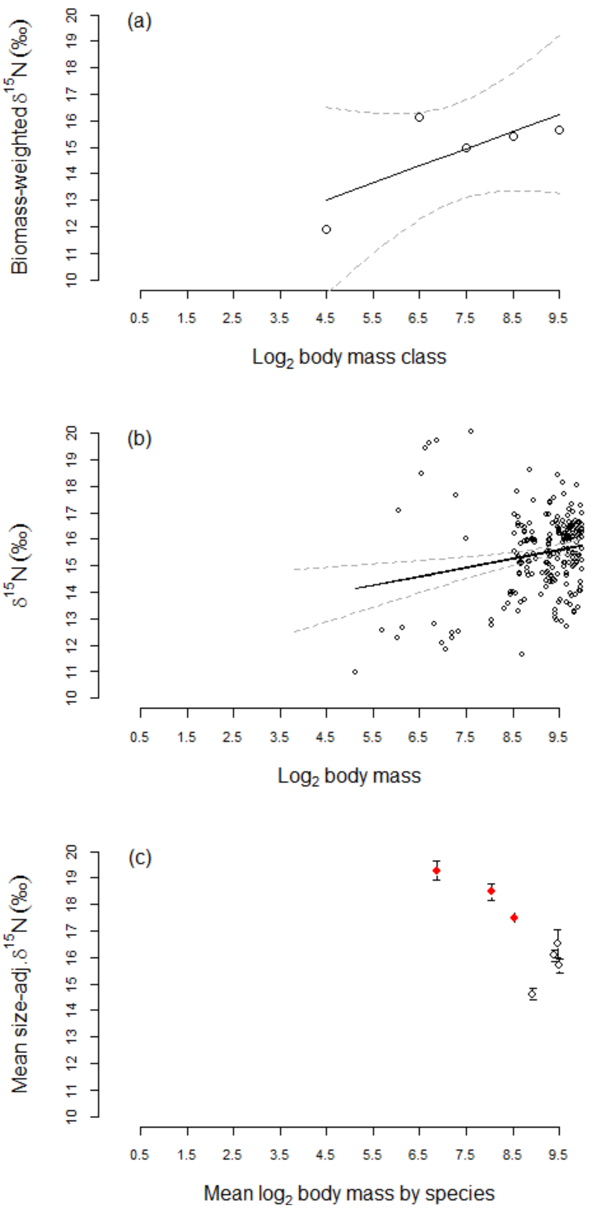

Figure 4. Relationships for fish communities in mesobenthic (>200 m) habitats between trophic level ($\delta^{15}N$) and (a) log2 body mass, (b) log2 body mass with individuals grouped by size class (nmin= 5 per size class), and (c) mean log2 body mass with individuals grouped by species. Mean $\delta^{15}N$ was adjusted to median body mass to account for life-history and growth differences in species comparisons. Red circles in panel (c) illustrate species means for eelpouts (Lycodes spp.), which were decoupled from the rest of the size-structured community.

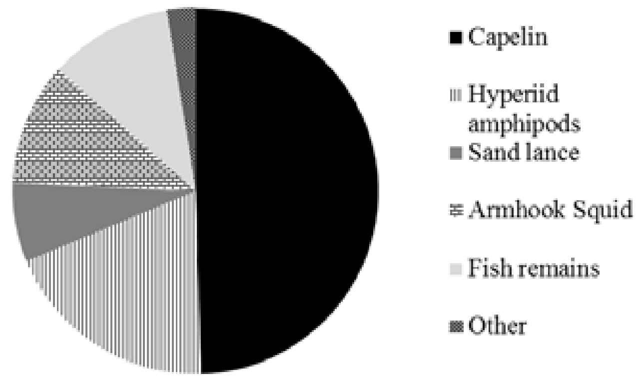

Figure 5. Abundance (% weight) of gut contents of Atlantic salmon caught at three communities off the West Greenland coast between 2009-2011.

developed the Salmon at Sea (SALSEA) West Greenland project, as a means to investigate salmon ecology at a location where both European and North American origin Atlantic salmon are known the feed. Over three years (2009-2011) and at three communities (Sisimiut, Nuuk and Qaqortoq) 1431 Atlantic salmon were sampled (Figure 5). Scales, dorsal muscle, adipose fin, liver and caudal fin samples were collected from each fish for stable isotope analysis, while gut contents were preserved either frozen or in 10% formalin. All stable isotope samples were sent to the University of Waterloo for processing. All frozen stomachs (~10% of stomachs collected) were also sent to the University of Waterloo for processing, while the formalin preserved stomachs were completed under supervised contract by Normandeau Associates, Inc., (Falmouth, MA. USA). Assembled samples were used to generate data for the completion of key methods studies (Completed Research Activity 4) and cutting-edge studies of marine feeding patterns within- and among-populations of West Greenland Atlantic salmon (Completed Research Activities 5 and 6).

The thematic analysis of all data sources resulted in 34 emergent themes, within three overarching themes of Program Operations, Community Perspectives and Effects on Program, and Considerations, Insights and Recommendations (Table 1). The emergent themes are

Table 1. Coding structure with overarching and emergent themes (n=34), resulting from the thematic content analysis. The right column shows the number of text passages assigned to each node. (32 sources of literature and expert interviews were analyzed in addition to all information resulting from the community collaborative research with the Sachs Harbour fishers.)

Themes	**Nodes**	**Total**
Program Operations	Cost and Funding Sources	50
	Methods	222
	Equipment and Tools Used	120
	Frequency and Timing of CBMP	49
	Length of Program	77
	Location of CBMP	85
	Parameters Sampled	134
	Purpose of CBMP	128
	Program Affiliations	64
	Community, Government or Industry Requested and Run	55
	Community Monitor Pay and Hiring Arrangement	93
	Reporting and Outreach	42
	Style of Community Involvement	59
	Style of Monitoring	110
	Traditional Knowledge (how included)	87
	Training	64
	Type of Fishery	49
	Who Does the Analyses (samples and data)	56
	Who Uses the Data	40
Community Perspectives and Effects on Program	Changes to Community Interests and Knowledge that Affect CBMP	82
	Community Engagement	74
	Community Interest in Program	38
	Community Involvement in Monitoring Design	93
	Community Perception of Monitoring Program	67
	Community Use of Char Resource	94
	Community Monitor Retention	49
	Results back to Community and Communication	27
Considerations, Insights and Recommendations	Benefits and Positive Attributes of Program	66
	Changes to Fishery that Affect CBMP	74
	Changes to Government or Decision-Makers that Affect CBMP	42
	Effectiveness of CBMP	26
	Outcomes and Influence of Outcomes	105
	Struggles and Challenges to Consider	274
	Recommendations and Considerations	363

used as the nodes for the coding structure in NVivo and are outlined Table 1, including the number of text references assigned to each node.

As part of the transfer of the Arctic Char CBMP to the community, the Sachs Harbour local monitors collected 128 Arctic Char samples from five studies lakes. The data collected included: length, weight, sex, maturity, otoliths (for ageing), parasites and stomach contents for diet analyses. These samples are currently in the lab analyses stage.

DISCUSSION

Previous research has documented that total mercury concentrations (THg) are lower in anadromous Arctic charr than in non-anadromous conspecifics (e.g. Riget et al., 2000; Evans et al., 2005; Swanson et al., 2011). Differences in THg are not related to differences in length-at-age (i.e., average somatic growth rate) among populations of either life-history type (van der velden et al., 2012a), but were hypothesized to be related to differences in THg at the base of the foodchain. Subsequent work on patterns of historical change (1977-78 compared to 2007-09) in THg concentrations in Arctic charr provided insufficient evidence to suggest there has been a widespread change in THg of anadromous or non-anadromous Arctic charr over the past thirty years, although the mean annual temperature increased by 1.6°C to 2.9°C between the two sampling periods (van der Velden et al. 2014). The lack of a widespread change in Arctic charr THg between 1977-78 and 2007-09 supports the general lack of consistent mercury temporal trends observed in studied Arctic biota over the past thirty years (Rigét et al. 2011). Results imply that mercury concentrations in Labrador lacustrine and marine fish habitats and prey resources have remained constant over the past three decades (Braune et al. 2011). Evidence from elsewhere suggests that the global atmospheric mercury pool, and therefore the rate of mercury deposition, has been relatively stable or declining in recent decades. Global anthropogenic mercury emissions to the atmosphere were in the range of 3500 ton/year during the late 1970s and early 1980s, but decreased during the 1980s to reach relatively stable levels of approximately 1900 to 2200 ton/year from 1990 to 2005 (Pacyna et al. 2006, 2010). Consequently, direct measurements of atmospheric mercury have indicated steady or declining concentrations since the 1970s at Canadian temperate and Arctic sites (Li et al. 2009; Steffen et al. 2005; Temme et al. 2007) and globally (Lindberg et al. 2007).

Continuing work on the mechanisms determining Northern Dolly Varden charr THg showed Northern Dolly Varden dorsal muscle tissue samples varied significantly among life-history types, with the anadromous life-history type tending to have greater absolute levels of THg (ng/g ww) than isolate or resident life-history types. Differences among the life-history types were correlated significantly with the stable isotope measures of feeding ($\delta^{13}C$) and trophic position ($\delta^{15}N$), with $\delta^{15}N$ being the more important variable for explaining differences within and among life-history types. Tissue THg concentrations increased significantly with size only among the anadromous fish, where they were also significantly negatively related to growth. Overall, among-individual differences in THg were best explained by life-history type, trophic position and growth rate, with differences in trophic position dominating as an explanation of among-individual variation in measured THg. In contrast to studies of other northern species such as Arctic charr, where anadromous life-history types have lower THg relative to freshwater conspecifics, anadromous NDV had higher absolute THg than their freshwater counterparts. Adjustment for age and length, however, indicated anadromous fish to have lower relative THg values. The reversal of ranks in terms of THg levels among life-history types ultimately depends on two counteracting mechanisms. The first mechanism raises overall THg as a result of the switch to marine feeding and the use of higher trophic level prey organisms that have previously bioconcentrated THg. The second mechanism lowers overall THg as a result of somatic growth dilution, whereby marine feeding allows fish to accumulate biomass faster relative to Hg and reduces standardized levels of THg relative to non-anadromous fish. The relative importance of differences between the THg concentrations in marine and freshwater habitats and prey, habitat-specific bioconcentration rates and/or differences in physiology related to anadromy that may contribute to the observed pattern of differences in THg among Northern Dolly Varden life-history types, however, remain an important area for further investigation.

Operation of the Nepihjee fishway in 2014 continued to yield quality data useful for studying the marine portion of the life-history in Arctic charr. Sampled biological data collected from the returns is being employed in on-going otoliths microchemistry analysis aimed at refining understanding of the effect of temperature on growth as published in previous work (e.g., Murdoch and Power 2103, Murdoch et al. 2014, Sinnatamby et al. 2014). To date insufficient data on temperature use by competitor species is available, but run-timing data indicate potentially competitive round whitefish appear to have a more protracted use of estuarine environments than Arctic charr, both arriving and leaving earlier that Arctic charr. Finally, while Arctic charr run numbers have settled in the 300-400 range, variability among-years continues, with an overall coefficient of variation on returns of 66.7%.

In Stewart Lake, repeat sampling of the fish community in the lake demonstrated significant changes in the fish community over time (1999-2014), with the relative abundance of round whitefish having declined markedly and the relative abundance of lake chub having risen. Changes in fish abundance were reflected in changes in fish condition, with average round whitefish having also declined in condition, while the average lake chub condition factor increased. Comparison of ^{13}C indicated that the two fish species showing the greatest changes in relative abundance (round whitefish and lake chub) also had the greatest overlap in carbon resource use. Lake chub are known to be temperature sensitive spring spawners (Darveau 2012), with spawning typically beginning as water temperatures rise above 10^{o}C (Stasiak 2006). Thus rising spring temperatures increase favourability of spawning conditions, increasing spawning success and associated juvenile survival. Competitive interactions with round whitefish driven by feeding niche overlap, in turn, reduced both relative abundance and condition of round whitefish. As a result of shifts in relative abundance, the following cascade effects are predicted, with increased use of Lake chub as prey predicted to lead to increased Hg concentrations in predatory Lake trout as a result of the significant differences in Lake chub (0.13±0.05 μg g^{-1}) and Round whitefish (0.09±0.03 μg g^{-1}) THg (Power et al. 2002). Collected tissue samples from 2014 are currently being used to test the hypothesis of climate-mediated changes in THg resulting from shifts in the relative abundance of fishes with the Stewart Lake community (Figure 6).

As part of a multi-agency research initiative, we have made significant progress in the collection and analysis of samples for characterising food web structure in the Beaufort Sea, and have also made significant progress in the statistical analysis and dissemination of initial results. Fisheries and Oceans Canada is tasked with the regulation of offshore oil and gas activities in the Beaufort Sea with the aim of minimizing impacts on marine fish and their habitats. To regulate effectively, regional baseline information must include both data on species distributions and habitat associations, but also on the trophic structure and energy pathways that support offshore ecosystems. Moreover, linkages between food webs in the offshore and near-shore areas must be better understood as they may be critical for overall ecosystem functioning. Work conducted in the 1970's and 1980's to understand the ecology of shelf and coastal/estuarine fish communities resulted in a basic understanding of inshore fishes and their habitats in the Beaufort Sea, but no comprehensive study of deeper offshore marine habitats and their associated fish communities has been completed. To that end, the work accomplished through our research will provide the first detailed descriptions of food web structure and function in the Beaufort Sea. Our research will not only address specific knowledge gaps regarding small-scale food web structure (e.g., trophic overlap between specific species), but will also address

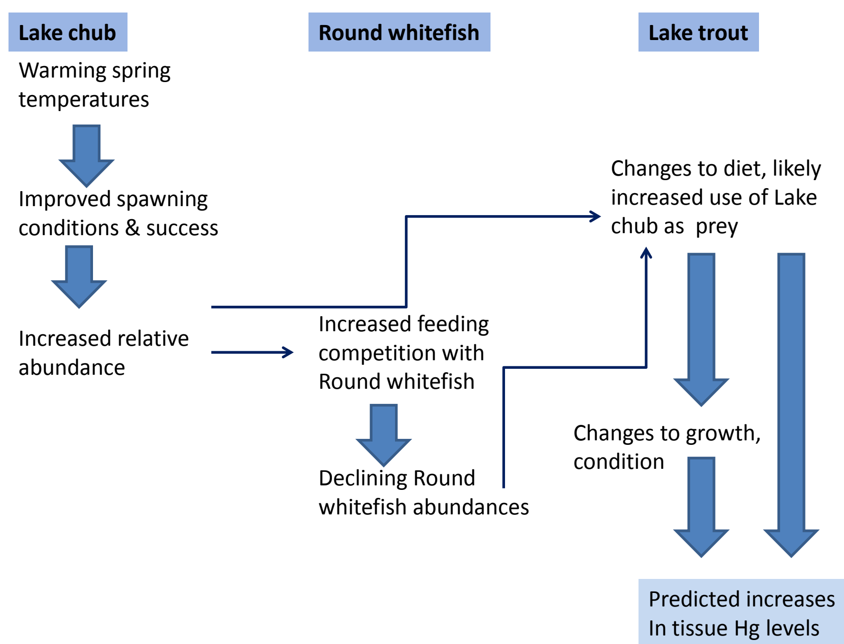

Figure 6. Linkages between changes in spring water temperatures, changes in Stewart Lake fish community and likely impacts on measurable THg in predatory Lake Trout resident in the Stewart Lake. Linkages illustrate how ecological change may trigger changes in contaminant levels independent of any change in local or atmospheric loading.

knowledge gaps pertaining to larger-scale ecosystem structure across the Beaufort Sea (e.g., benthic-pelagic coupling, effects of depth, effects of water mass structure, etc.).

An estimated 66 fish species occur in the Beaufort Sea, the majority of which are associated with benthic habitats (Christiansen and Reist 2013). Knowledge of the feeding ecology of most Arctic fishes, however, remains incomplete. Most current knowledge is derived from species that inhabit coastal areas (e.g., Atkinson and Percy 1992; Chambers and Dick 2007; Dolgov 2009) or are of interest to commercial and subsistence fisheries (e.g., Greenland halibut *Reinhardtius hippoglossoides*, Ackman et al. 1967; Arctic cod *Boreogadus saida*, Walkusz et al. 2011; Arctic charr *Salvelinus alpinus*, van der Velden et al. 2013b), leaving much unknown about the feeding ecology of species that occur primarily in offshore habitats. These lesser known species are of considerable ecological importance and some have been shown to constitute a large part of the diet of top predators such as marine birds (Springer et al. 1984), ringed seal (*Phoca hispida*; Andersen et al. 2004), bearded seal (*Erignatus barbatus*; Finley and Evans 1983), narwhal (*Mondon monoceros*; Finley and Gibb 1982), and beluga whales (*Delphinapterus leucas*; Loseto et al. 2009).

Using multi-tracer dietary methods we characterised trophic variability among three common Arctic fish families. We documented specific trophic pathways exploited by each species, and provided one of the first quantitative analyses of intra-family dietary partitioning for these species in the Beaufort Sea. Although some of the species analysed share the same habitat and likely the same availability of food resources, there was little support for strong interspecific trophic overlap among demersal fishes in this study. Most interestingly, we found evidence of pelagic contributions to the diets of most demersal fish in our study, even those found as deep as 1000 m and those that likely feed on benthic prey. Pelagic production could be transferred to demersal fish through the consumption of herbivorous pelagic prey that migrate periodically to the benthic zone (e.g., *Calanus sp*. copepods or Arctic cod), or through the transfer of energy from sinking phytodetritus into biota at higher trophic levels. We conclude that strong benthic-pelagic linkages are important for maintaining deep-sea fish communities in the Beaufort Sea, with implications for the effect of changing surface production (e.g., from climate change, increased shipping, etc.) on the food webs.

More broadly-based analyses of foodweb structure in the Beaufort was completed using tools developed for assessing abundance-body size relationships (size spectra) of whole communities that can be used to quantify anthropogenic impacts on marine food web structure (Jennings and Blanchard 2004), and would be especially useful in the Arctic where species-based analyses are complicated by limited knowledge of taxonomy. Moreover, quantification of size spectra can provide information on ecosystem function such as the efficiency of energy transfer up the food chain and predator-to-prey body mass ratios. Our preliminary results indicate that while fish communities in the Beaufort Sea are size structured, size spectra slopes are much steeper than those estimated in historical reconstructions of unexploited North Sea fish communities (slopes of -0.1 to -0.2 compared to -1.32 to -0.84 in the Beaufort Sea; Jennings and Mackison 2003; Jennings and Blanchard 2004). Steeper slopes are indicative of lower energy availability to larger size classes. It may therefore be possible to use size spectra to quantify anthropogenic impacts as had been done in the North Sea, but Beaufort-specific models must first be developed.

Our preliminary results also revealed that several species of eelpouts are decoupled from the energetic transfers structuring the rest of the community. While most species increase in trophic level with increasing size, *Lycodes* spp. decrease in trophic level. A decrease in trophic level with size is likely a result of feeding on detritus or bacterial-based food chains in early life (Bjelland and Bergstad 1998), which often have elevated $\delta^{15}N$ values due to extensive carbon recycling on the seafloor. Future attempts to model Beaufort size spectra will thus need to carefully identify additional subsets of the community that are not coupled to the size-structure food web (e.g., detrivores and filter feeders). Overall, we expect these analyses to support both hypotheses (listed in results) and provide a quantitative index of trophic energy efficiency in deep-sea communities that may be used as a benchmark against which future monitoring in the Beaufort Sea may be compared. A size-based index would be especially useful given the constraints on taxonomic resolution in the Arctic.

In studies of Atlantic salmon (*Salmo salar* L.) ecology, scale samples have been used to assess trophic interactions and migrations. The use of scales is complicated by their architecture and growth, with later overplating layers covering the lower older layers and biasing their isotope values. Despite the increase in scale use, there is no consensus as to what part of the scale should be used for stable isotope studies. Here, the stable isotope values for the marine growth zone of scales and its constituent growth zones (1st summer, 1st winter, 2nd summer) from non-maturing 1SW Atlantic salmon are investigated. Significant differences were found between the different sections of the marine growth zone, which, although small, were comparable to differences interpreted as biologically significant by other stable isotope studies. A mathematical model assuming isometric growth was used to correct for the biasing effect of later overplating. The method facilitates calculation of the "pure" stable isotope values for the different marine growth zones, and a "pure' value for the whole marine growth zone. As the 1st summer section suffers from the highest amount of overplating, it suggests that the differences between the "pure" and measured values should be highest for this section, rather than for the 1st winter. However, differences in diet between seasons could potentially be responsible for this discrepancy. Templeman (1967, 1968) found differences between Atlantic salmon feeding in summer 1965 and winter 1966, with a Schoener's index showing 9.9 % overlap by volume. Differences between the growth zones may be a reflection of varying influences of pelagic and littoral energy sources, particularly between the "pure" 1st winter and 2nd summer sections. Atlantic salmon feeding in the coastal waters in the 2nd summer, such as Greenlandic fjords, may be exposed to terrestrial-sourced carbon from inputs from estuaries and glacial melt (Rysgaard et al., 2003; Mernild et al., 2010; Liston and Mernild, 2012), resulting in a different SI value from salmon feeding purely within the pelagic oceanic ecosystem, such as during the over-wintering period in the Labrador Sea. Appropriate accounting for the differences between measured and "pure" values will assist in minimising the ecological inferential associated with the use of stable isotope analysis. Given the similarity between the measured and "pure" whole marine growth zone values, the measured whole marine growth zone can be used as a proxy for average marine feeding, the whole marine growth zone has SI values for $\delta^{13}C$ and $\delta^{15}N$ that are closer to the 1st summer than the 2nd, suggesting that the marine growth zone is largely a reflection of diet and environmental conditions the salmon experience as post-smolts. The post-smolt stage is the fastest growing of the marine life-history stages, and the most important in terms of salmon growth and subsequent recruitment (Rikardsen et al., 2004; Friedland et al., 2006; Peyronnet et al., 2007; McCarthy et al., 2008). The commonly used 2nd summer growth zone was found not to be representative of earlier marine feeding.

Atlantic salmon diet has been poorly studied in the Northwest Atlantic when compared with information available from the Northeast Atlantic. Climate change induced changes to food webs in the marine feeding areas for Atlantic salmon have been noted, along with an increase in Atlantic salmon mortality despite a cessation in most ocean fishing activities. Since forage success may be hampering salmon survival, it was important that this knowledge gap be addressed. Accordingly, Atlantic salmon were sampled at three communities on the West Greenland coast (Sisimiut, Nuuk and Qaqortoq) across three years, in 2009-2011. Conventional gut content analyses were combined with stable isotope methods to assess spatial and temporal differences in salmon feeding. Capelin (*Mallotus villosus*) was found to be the dominant prey species overall, with hyperiid amphipods (*Themisto spp*.), boreoatlantic armhook squid (*Gonatus fabricii*) and sand lance (*Ammodytes spp*.) also featuring heavily. Significant differences were found among communities for both gut contents analysis and stable isotope analysis, and among years for stable isotope analysis, along with differences evident across larger spatial and temporal scales. Results showed that Atlantic salmon diets have changed over the last 40 years, particularly with the emergence of squid as a prey item. All communities had boreoatlantic armhook squid present in 2009-2011, while it had been completely absent from the West Greenland coast in 1968-1970 (Lear, 1972, 1980). While there was some similarity in salmon feeding patterns at several West Greenland locations, with that shown historically by Lear (1972, 1980), Sisimiut demonstrated a significantly lower overlap due to the reliance on squid at this location. Boreoatlantic armhook squid favour warmer temperatures and more saline waters, and has only recently been recorded in the Sisimiut area (Golikov et al., 2013). The shallower bathymetry and the higher presence of temperate, saline Irminger Water in the bottom coastal waters off Sisimiut (Ribergaard et al., 2010) may have led to ocean conditions becoming more suitable for squid. Since the historical data were collected, atmospheric and oceanographic changes in the Arctic and Northwest Atlantic have led to changes in the biogeography of the region (Wassman et al., 2011; Buren et al., 2014). Of primary concern for Atlantic salmon diet is a reduction in abundance and changes in the distribution of capelin stocks in the mid-1990s (Livingston and Tjelmeland, 2000; Carscadden et al., 2001, 2002; Bundy et al., 2009; Dwyer et al. 2010; Buren et al. 2014).

When compared to information from salmon diet in the Northeast Atlantic, Atlantic salmon feeding at West Greenland were found to have broadly similar preferences for fish, crustaceans, and squid, although the species present were significantly different. A reliance on fish forage species is profitable for Atlantic salmon, given that these prey taxa are often more energetically beneficial to them, with higher energy densities and lipid contents (Lawson et al., 1998; Rikardsen and Dempson 2011). Capelin was the most important prey item in Atlantic salmon diets at Nuuk and Qaqortoq, while at Sisimiut squid were more important. Evidence of specialisation on these prey items at these communities was apparent. By gaining an understanding of Atlantic salmon diets and the variation thereof, an insight can be gained into the possible effects of food web changes on this species.

Community Interests and Perspectives on Arctic Char CBM:

Interviews with operators and others involved in Arctic char community-based monitoring programs across the north provided valuable insight into the interest in these programs and recommendations for their operation. Interviews identified:

- The interests in such programs were in immediate benefits of such programs, such as answers to current pressing questions.
- Community-based monitoring programs were mostly seen as a distraction from traditional harvesting practices so fishers felt there should be dedicated Arctic Char monitor(s) as opposed to adding these activities to harvesters' responsibilities.

Interview participants identified changes in community economies and activities that influence the operation of such monitoring programs. They identified:

- People did not go out on the land as much as they used to and the wage earning economy resulted in people having busier schedules. Fishing and harvesting now occurred mostly evenings and weekends.
- As information became accessible through the internet, new concerns were introduced to communities (e.g. contaminants). Local experts wanted these new parameters included in CBMPs as their knowledge of these topics grew.

Finally, they identified changes to the fishery that have implications on CBMP now and in the future as well:

- Sachs Harbour fishers asked to include the nearshore marine fishery in their CBMP due to low numbers of Arctic Char over the past two years. The plan devised with the SHHTC was to hire two paid community monitors to sample Arctic Char caught in subsistence fisher's nets. However, few nets were set due to an unexpected abundance of seals. This meant no samples or data could be collected for the CBMP.
- In Paulatuk, the outlet of the Hornaday River shifted due to melting permafrost and erosion, and is now further away from the community and harder to access. Local fishers relocated their fishing to the Brock River and as a result the community suggested the need for a new Arctic Char CBM site.

The community of Sachs Harbour is trained and fully capable of taking over the Arctic Char community-based monitoring program. The transfer of the Arctic Char CBMP designed through this research to the community of Sachs Harbour was a success. The local monitors were able to continue on their own the sampling of char from the studies' lakes collecting all biological parameters. However, on-going financial and laboratory support will be required to ensure the continuation of this project. On a positive note, the FJMC is now looking to create and support a Sachs Harbour Arctic Char Working Group in their efforts and are looking to incorporate knowledge gained through this research into Working Group decision-making.

CONCLUSION

Completed work in 2014 successfully met its key objectives via the continued construction of long-term time series data on Arctic charr migration and growth in the Nephigee River (Ungava Bay), the completion of supplementary sampling for the analysis of Beaufort Sea foodwebs, the continued use of mercury analysis methods to document temporal changes in lacustrine foodwebs in lakes used for recreational fishing proximate to Kuujjuaq, and the continuation and expansion of initiatives begun in the western Arctic to document THg in Dolly Varden Charr and Arctic charr marine tagging initiatives in the eastern Arctic. Supplementary studies of Atlantic salmon in the Arctic marine environment (West Greenland) and of Arctic charr genetics have further led to significant improvement in our understanding of both species and their Arctic ecology. From the work we have learned the competitive overlap between Arctic charr and other potentially anadromous species (e.g., round whitefish) is temporally limited. Continuing studies of THg in fish in the Arctic revealed interesting patterns of differences within populations and through time. In the study of Dolly Varden Charr, continuous freshwater residents were found to have lower levels of THg than co-occurring anadromous fishes. The pattern is the reverse of that observed for Arctic charr in the eastern Arctic and is related to critical differences in the physical habitats occupied. In Stewart Lake, critical changes to THg dynamics were predicted on the basis of climate-change triggered changes in the fish community that have seen the decline of previously important prey species for lake trout. In the Beaufort we have begun to understand the trophic overlap within and between families of fish, noting that the diets some species vary spatially (e.g., Arctic Alligator fish) whereas others do not (e.g., eelpouts). Nevertheless, further studies are needed to assess the effect of depth and other environmental variables on the dietary patterns of Arctic marine fishes. Although some of studied fish species shared the same habitat and food resources, there was no strong evidence of inter-specific overlap in diet among benthic fishes for prey. We have also been able to demonstrate the that fish communities in the Beaufort Sea appear to be size-structured, with abundance-body mass relationships in Arctic marine habitats that are steeper than those in other studies marine habitats (e.g., North Sea), suggesting that the energetic transfer between trophic steps is less efficient in Arctic marine food webs.

In regards to the work conducted under this project on the environmental effects on char growth and the development and implementation of community-based char monitoring programs the approach used in this study has not been used in this context before and the outcomes provide novel insights into needs and considerations for effective Arctic Char community-based monitoring from the community perspective. Emergent themes identified areas of consideration for success of an Arctic Char CBMP in Sachs Harbour including: changes to community fishing practices; changes to community interests and perceptions of monitoring needs; and, changes to perceptions of the CBMP.

Inuvialuit are resilient and have continuously and rapidly adapted to changes in their environment, culture and lifestyle. The community of Sachs Harbour was so adaptable in their use of the Arctic Char resource, their interests and use of the resource could shift rapidly, resulting in the potential need to adapt monitoring regimes without notice. Therefore, an Arctic Char community-based monitoring program for Sachs Harbour needs to take an adaptive monitoring approach in order to continuously address the developing needs of the community in managing the resource in a rapidly changing environment. An adaptive monitoring framework enables monitoring programs to maintain core data collection while allowing the CBMP design to evolve iteratively as new information emerges and questions change (Ringhold et al., 1996).

With the groundswell interest in community-based monitoring worldwide, Arctic communities and partner organizations need to know they have a program design that will produce legitimate results while still being able to address shifting community needs in order to maintain effective long term CBMPs. Community approaches to monitoring and use of the resource need be thoroughly understood when designing an Arctic Char CBMP.

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FRESHWATER RESOURCES OF THE EASTERN CANADIAN ARCTIC

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Microbial oxygen dynamics in permafrost thaw lakes
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Les grands incendies du Haut-Boréal et le climat depuis deux siècles au Québec nordique

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Construction de séries dendrochronologiques millénaires à partir d'arbres puisés dans les lacs du Nord de la forêt boréale
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The role of ocean dynamics and meltwater input on the fate of the Milne Fjord ice shelf, glacier tongue and epishelf lake, Ellesmere Island
Alex Matveev, Doctoral Student (Université du Québec à Montréal)
Development of thermokarst lake parametrization for climate models
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Paleoclimates and paleoenvironments of the Nettilling Lake region (Baffin Island, Nunavut, Canada), as inferred from isotopic and sedimentological analyses
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Mass balance and the spatial variability of accumulation on White Glacier, Axel Heiberg Island, Nunavut
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Reconstitution dendroisotopique du climat au Labrador au cours des deux derniers siècles
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Dendroclimatologie du pin gris et histoire des périodes sèches en Jamésie
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Paleoclimatic reconstruction of the central Baffin Island region, Nettilling Lake, Nunavut
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Detection of ice islands using Radarsat-2
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ABSTRACT

Freshwater lakes and wetlands are abundant in the circumpolar Arctic, and still more freshwater is present in the form of glaciers and ice shelves. These freshwater environments provide many essential services including habitats for aquatic wildlife, drinking water for northern residents, and hydroelectricity. Inuit communities and northern scientists have increasingly observed that these resources are highly vulnerable to ongoing climate change. This project extends our observations on lakes and wetlands at key sites in the eastern Canadian Arctic, to identify and measure aquatic indicators of environmental change in the past and present. These studies are allowing us to make assessments of future changes in northern freshwater ecosystems to help guide the formulation of environmental management and monitoring policies. We are continuing our research on lakes, ice shelves and contaminants along the northern Ellesmere Island coastline based out of Ward Hunt Island Observatory, where we work with Parks Canada to develop facilities, indicators and protocols for long term monitoring. This coastline lies at latitude 83°N, at the northern limit of Nunavut and thus North America, and it is characterized by many climate-sensitive aquatic ecosystems that are highly dependent on ice. Discharge from glaciers also contributes to iceberg flux, which is important for shipping. We are extending our research to wetlands by assessing the snow storage and melt patterns in Polar Bear Pass on Bathurst Island (75°N). This Wildlife Sanctuary is composed of a mosaic of lakes and ponds, and seasonal snowmelt is considered the most important source of water to this wetland. The resultant models and understanding should be of broad application to arctic wetland wildlife habitats that have begun to respond strongly to climate change. Permafrost thaw lakes are a prominent component of northern wetland ecosystems, and we are working at several sites including Bylot Island (73°N) and Kuujjuarapik (55°N), to determine the environmental factors that control their ecosystem metabolism and net production of greenhouse gases in the present and future. This ArcticNet research is in collaboration with the Discovery Frontiers program ADAPT (Arctic Development and Adaptation to Permafrost in Transition), which involves 15 laboratories across Canada. We are analyzing sediment cores from northern waters in the Foxe Basin region (65-70°N), as well as on both sides of Hudson Bay, to assess the natural climate variability in arctic and subarctic Canada, and to identify regional variations in climate sensitivity. Additionally, we are documenting past climate changes in the eastern Canadian subarctic by way of an extensive network of tree-ring analysis sites. Finally we are developing and applying new DNA-based techniques to assess the diversity and function of microscopic life in lakes and wetlands and to develop state-of-the-art molecular indicators of climate responses by northern aquatic ecosystems. We are contributing our findings and expertise on Canadian arctic water resources to the ArcticNet IRISs, Canadian and pan-Arctic climate impact assessments (for example, the SWIPA report), government agencies such as Transport Canada and the Canadian Wildlife Services, and circumpolar initiatives such as the 'Arctic Freshwater Synthesis' under the auspices of the International Arctic Science Committee (IASC). Furthermore, we will document past climate change in the eastern Canadian Subarctic by means of a vast network of millennial dendroclimatic series.

KEY MESSAGES

Groundwater flow pattern of wet meadows at Polar Bear Pass (PBP) is driven by rainfall inputs during wet periods, while aquifer characteristics (soils, thickness of the water layer) modify rates in drought conditions. Groundwater inflow into tundra ponds is not important during the summer season (post-snowmelt season), even when there is a source of additional meltwater from upslope late-lying snowbeds. Rather, summer pond levels are dominated by the interaction of summer precipitation inputs versus evaporation losses.

- The great variability in geomorphological and limnological conditions of the abundant ponds and lakes characterizing permafrost landscapes leads to a large range and different seasonality in their greenhouse gas emissions. Ponds and lakes of the eastern Arctic are emitting ancient carbon and could act as a positive feedback mechanism on climate.
- A substantial proportion of the microbial community in subarctic thaw ponds consists of methane-producers. The microbial community of these water bodies is diverse, and affected by environmental and stochastic processes.
- There has been rapid recent breakup of the termini of many tidewater glaciers along the northern coast of Ellesmere Island, which appears to be related to the loss of multi-year landfast sea ice. For example, a ~10 km long section of the floating terminus of Yelverton Glacier has broken up in the past 5 years. The discharge of icebergs from glaciers in the Canadian High Arctic is highly focused in a few fast-flowing outlet glaciers, with the Trinity-Wykeham glacier complex of eastern Ellesmere Island currently supplying ~50% (~1.3 Gt/yr) of all Canadian iceberg flux to the oceans.
- In contrast to rapid glacier break up, the Milne Fiord epishelf lake, which has diminished drastically in thickness over the past several years, did not change substantially during 2013 and 2014, and there was not major ice-out at Ward Hunt Lake.
- Contrary to previous assumptions, the central portion of the Milne Ice Shelf is composed primarily of brackish 'basement' ice, which was formed by basal freeze-on. This suggests that the surface of the ice shelf has drastically ablated in recent decades or that glacial input is not as important to the mass balance of the ice shelf as previously thought.
- Polarimetric Synthetic Aperture Radar (SAR) offers some improvements in separating ice islands from other ocean cover types (sea ice and open water). However, results are only reliable for supervised classification. More research is necessary to reliably detect ice islands using SAR imagery.
- The instrumental records of water supply in the area of hydroelectric production in northern Quebec indicate that there has been two major periods, one of strong hydraulicity in the 1960s and 70s, followed by a long period of weak hydraulicity in the 1980s and 90s. The economic value of the standard deviation around the mean water supply, in terms of hydroelectricity production, is about $1.5 million, hence the unpredictability in the production has important consequences.
- Along the millenial record of past hydro-climatic variations, tree-rings revealed that the main forcing for hydraulic changes are the volcanic eruptions that had a global effect on solar irradiance. After such major eruptions (Gennaretti, Arseneault & Begin 2014, PNAS) low hydraulicity is recorded for up two time stretches of two decades.
- Assemblage shifts in the diatom community show that lake desiccation in a subarctic thermokarst pond (Puddle Pond, Manitoba), associated with precipitation changes and low snowmelt runoff, is unprecedented in recent centuries. Lakes in sporadic permafrost terrain experience

greater desiccation than lakes in discontinuous permafrost terrain.

- The replacement of picoeukaryote prey organisms by cyanobacteria because of rising temperatures in thaw ponds and lakes may reduce the growth rate of cold-adapted zooplankton.
- Thermokarst ponds are anoxic through most of the year and rich in methane. Bacteria that oxidize methane to CO_2 (methanotrophs) are unusually abundant in these ecosystems and may regulate the net fluxes of greenhouse gases to the atmosphere.

OBJECTIVES

- Continue running the northernmost weather station in Canada with near real time data access at Purple Valley, Ellesmere Island (see http://tinyurl.com/milnewx), and the longest mass balance monitoring program in Canada at White Glacier, Axel Heiberg Island.
- Determine water budgets for tundra ponds and wet meadows in Polar Bear Pass.
- Measure greenhouse gas emissions from thaw lakes and ponds in eastern subarctic and arctic regions, considering the seasonality, the different modes of emissions (diffusive flux versus ebullition) and the age of emitted carbon.
- Investigate the controlling factors on greenhouse gas emissions from thaw lakes and ponds, including the surrounding geomorphological conditions, contrasting permafrost regimes (isolated, sporadic and discontinuous), the pond physical structure, oxygen stratification and other limnological characteristics, and microbial biodiversity and function.
- Distinguish the effects of geographic proximity and landscape type (southern highly degraded versus northern discontinuous permafrost) on microbial communities in thaw ponds by evaluating microbial diversity at different spatial scales.
- Characterize the lability of the different carbon pools present in the ice wedge polygon landscape of the eastern Arctic that are mobilized by permafrost thawing and become available to aquatic systems.
- Improve understanding of the connections between sea ice, ice shelf and glacier losses across northern Ellesmere Island by quantifying the temporal variability in glacier velocities, measuring thickness of tidewater glaciers, and quantifying iceberg fluxes to the ocean across the Canadian High Arctic.
- Investigate the processes of drift and deterioration of ice islands in Arctic waters as well as their ecological impact and examine the influence of a grounded ice island on the physical, chemical and biological oceanography near Resolute Bay, Nunavut.
- Explore polarimetric Synthetic Aperture RADAR (polSAR) as a new method to detect ice islands and identify unique ice types along the northern coast of Ellesmere Island.
- Provide the first comprehensive oceanographic description of the Milne Fiord system, including modeling the basal melt rates of the Milne Ice Shelf as well as the Milne Glacier terminus and floating glacier tongue, characterizing the thickness, velocity and grounding line dynamics of the Milne Glacier, and evaluating the hypothesis that the Milne Fiord epishelf lake drains under the Milne Ice Shelf in channels that could destabilize this massive ice feature.
- Study all available proxies (dendrochronology, isotopes, density, growth, varves, historical archives) that can be used to extend the instrumental series toward the past, to test their representativeness, and to reconstruct key hydroclimatic variables useful for modeling river and lake hydrographs in the area of hydroelectric production (present and projected) in northern

Quebec for a period exceeding the last two centuries. Some of these proxies can also be used later on to expand the study area to the regions covered by other IRISes of ArcticNet.

- The ARCHIVES project also aims to compare these reconstructions to the outputs of the CRCM and ARPEGE-Climat models, which are reconstructed for the 50-year instrumental period of reference, and to distribution statistics modeled for the last 150 years, in order to test the reliability of the climate models and to identify which forcings affect the hydroclimatic variations in the study area. The objectives were (1) to complete data acquisition and homogenization of data banks and (2) to compare climate simulations and reconstructions.
- Develop an inventory of the different substrate and habitat types that exist in thermokarst lakes and ponds to characterize the composition and biodiversity of their algal (diatom) communities, and gain insights into the evolution (or "life cycle") of these increasingly abundant freshwater ecosystems through the recovery of sediment cores, thereby establishing the temporal framework for the reconstruction of the limnological conditions over past centuries.
- Determine the present-day sedimentological, geochemical and isotopic characteristics in the sediments and water column of thermokarst ponds and lakes by analyzing the settling particles (mineral and organic) collected in sediment traps, to better understand their hydrological settings and behavior.
- Characterize the temporal chemical variations (including metals) in thermokarst lake sediments and water columns of the Hudson Bay region, with the particular goal of estimating the availability and bio-accumulation of metals in aquatic and terrestrial plants.
- Investigate the direct effect of temperature and indirect effect of subarctic picocyanobacteria (*Synechococcus*) versus eukaryotic prey on threshold food concentrations and growth rate of a high latitude *Daphnia* clone.
- Determine the methanotrophic bacterial composition of thermokarst lakes and ponds.

INTRODUCTION

This project examines the range of aquatic resources of the eastern Subarctic and Arctic Canada, their biodiversity (with emphasis on microbial communities), ecosystem structure, hydrological and biological functioning and potential ecological responses to climate change. Additionally this project includes studies of glaciers, fjords and ice shelves of High Arctic Nunavut, which are sentinels of climate change and that also play a major role as aquatic environments for unique ecosystems. Via the close collaboration in ADAPT (Arctic Development and Adaptation to Permafrost in Transition), the project is developing an integrated systems perspective on freshwater ecosystems in landscapes underlain by permafrost. Via the contribution ARCHIVES, this project includes studies on the paleohydrology of high latitude environments, specifically by the use of tree ring analysis (dendrochronology) from wood samples retrieved from subarctic lakes.

Polar Bear Pass (PBP), located in the central part of Bathurst Island, is a 100 km^2 wildlife sanctuary which provides food and shelter for migratory birds, and grazing caribou and muskox. It is an important hunting ground for Inuit. Wetlands in this region provide important ecosystem services, as they do across the Arctic. We are conducting hydrological studies of tundra ponds and wet meadows in PBP to understand how they are being impacted by declining snow cover.

Permafrost thaw lakes, also called thermokarst lakes, occur in high abundance across the subarctic landscape, and can potentially emit CO_2 and CH_4 to the atmosphere, often acting as conduits to ancient labile organic carbon deposits in deeper layers of permafrost.

Emissions are controlled by a combination of factors, including geomorphology, limnological characteristics and microbial ecology. For example, shallow ponds become well stratified during summer, creating a bottom low-oxygen or anoxic layer that favours methane-production by microbes. Given the important role of microbes in greenhouse gas production, a greater knowledge is needed about the limnological dynamics and microbial diversity in the water columns of these ponds. Our ongoing investigations on various aspects of thermokarst lake ecology, limnology and paleolimnology in the eastern Hudson Bay region of Nunavik aim at providing a better understanding of these processes. Knowledge of current and past diatom assemblage in thermokarst ponds can give indications of trends in environmental conditions.

The mass balance of ice shelves, glaciers and ice islands is a visible and dramatic indicator of climate change, as well as being immediately relevant to shipping activity because of icebergs. Measurements from the GRACE gravity satellite indicate that the Canadian High Arctic has been losing glacier mass over the past decade at the highest rate of any glaciated region of the world outside of Greenland and Antarctica. The total area of ice shelves on northern Ellesmere Island has halved since 2005. The Milne Ice Shelf is notable because it forms the seaward limit of the Arctic's only epishelf lake. Meltwater that flows into Milne Fiord enters the epishelf lake and must eventually flow to the Arctic Ocean. It is plausible that this outflow has the capacity to incise channels into the ice shelf and thereby reduce the thickness of the epishelf lake while simultaneously weakening the ice shelf as posited by Mueller et al. (2003). The Milne Glacier is a large outlet glacier that has been observed to surge in the past (Jeffries 1984) and this may relate to dynamics at the grounding line and changes in thickness over its length. Our research focused on the changing morphology of these features, as well as their influence on surrounding ecosystems.

The interannual variability of water supply has important consequences for natural ecosystems. Several years of low water levels may lead to a regressive succession in the vegetation and to a significant modification of the interactions between populations of organisms. High water levels also have consequences, in particular when they occur in the presence of ice; in many watercourses, ice jams have major impacts on riverbanks. Population growth in the North, modernization of water supply using artesian wells, shallow wells, or river intakes, and channelling of flow in aqueducts and sewers; these factors call for a management of the water supply and demand. This is also true for the water used to produce electricity since the demand is currently only a few percentage points below the production capacity. These are major issues in the North where precipitation decreases with latitude and mostly falls in solid form. The objective of the ARCHIVE project is to use fossil trees to understand the spatial and temporal variability of water supply within the context of climate change in order to suggest adaptation strategies for natural and anthropized systems.

In thaw ponds and lakes, zooplankton, including crustaceans and rotifers, usually form the top of the short food web. One predicted effect of climate change on thaw pond food webs is the potential shift in phytoplankton community structure towards increased cyanobacterial abundance. Given that cyanobacteria are known to be a nutritionally poor food source, such a shift might reduce the efficiency of feeding and growth of northern zooplankton, with implications for the diversity of cold-adapted species. We tested this hypothesis in an experimental system.

ACTIVITIES

- Although no new fieldwork was carried out at Polar Bear Pass (PBP) this season, video and climate data were downloaded from the main Automatic Weather Station (AWS), and some photographs were taken in early July 2014.
- Several lakes and ponds on Bylot Island, Nunavut were sampled in July 2014 to measure

their greenhouse gas (GHG) emissions through diffusion and ebullition. Diffusive fluxes are estimated from dissolved gas concentrations (n=64) and modeling of gas exchange coefficients, and ebullition fluxes (n=18) from submerged funnels. Funnel gas samples were investigated for their gas concentration, isotopic composition ($\delta^{13}C$, $\delta^{2}H$) and ^{14}C age. Thermistor chains were installed for the whole year (July 2014-July 2015) in two ponds, one including an oxygen sensor placed at the bottom. Incubation experiments were done on a series of permafrost soil and lake sediment samples to investigate the lability of carbon to microbial degradation, measuring their GHG production and oxygen consumption over two weeks. One set of experiments was done in the field (shaded conditions, in situ temperature) and another set back in the lab under controlled conditions (dark, 4°C). Soil and lake sediment samples were analysed for C/N, percentage of organic matter and ice/water content.

- Samples were collected at Ward Hunt in July 2014 for DNA/RNA, basic limnological variables, zooplankton, HPLC and microbial mats. These samples came from snow, the surface and bottom of the lake, the lake outflow, water tracks, a lagoon, and the Arctic Ocean. Respiration by particle-attached and free-living bacteria was measured in lakes and ponds in the Kuujjuaraapik region, along with basic limnological variables, oxygen, CO_2 and CH_4 concentrations. DNA/RNA samples were collected from the water column, sediments, and microbial mats. Data was downloaded from a mooring, which was then redeployed for another year of continuous automated measurements. A new flow cytometry system was implemented to obtain cell-count data from samples from lakes and ponds.
- A clone of *Daphnia pulex* from a permafrost thaw pond in subarctic Québec was investigated in an experimental system.
- Weather stations on the Milne Ice Shelf were updated with new sensors and equipment. Four new time-lapse cameras were installed at three existing weather stations to record the gradient in fog conditions and snowfall from the seaward to inland boundary of the ice shelf, while two additional cameras were also installed on cliffs overlooking the ice shelf to assist with this monitoring. A new wind sensor was installed at one weather stations on the Milne Ice Shelf to improve understanding of interactions between snow accumulation patterns and wind conditions.
- Mass balance stakes on White Glacier (Axel Heiberg Island) and the Milne Ice Shelf (Ellesmere Island) were measured to continue the long-term monitoring of glacier health across the study region. The position of the stakes was also measured with a portable differential GPS system to measure ice motion and provide validation for remote sensing imagery. A 10-m deep ice core and snow samples from a 100-1500 m elevation transect across White Glacier were collected for oxygen isotope analysis to assess whether temperatures and snowfall patterns have changed across this region since similar measurements were last made in the 1970s.
- Water samples were collected from thermokarst lakes located between Whapmagoostui-Kuujjuarapik and Rivière Nastapoka (Nunavik), at four different “ADAPT super-sites” (SAS, KWK, BGR and NAS), from site SAS in the South to site NAS in the North, to study hydrological settings and principal hydrological components influencing their water balance using lake water isotope composition ($\delta^{2}H$, $\delta^{18}O$). Sediment cores were retrieved from 12 thermokarst lakes for paleohydrological study of these lakes using oxygen isotope composition of cellulose. Sediments were retrieved from an automated sediment trap installed in 2013 in the lake BGR-A and an additional sediment trap also measuring optical properties was re-deployed to continue monitoring sediment dynamics of the lake and to provide annually settling material

(organic and mineral) that we will analyse for its physical and geochemical properties (MSc student Olivier Coulombe, co-supervision with Frédéric Bouchard).

- Building on recently published work dealing with sedimentological dynamics in subarctic thermokarst ponds (Bouchard et al. 2014; Arctic, Antarctic & Alpine Research), we initiated a new project with focus on the impacts of landscape evolution on the limnological and sedimentological dynamics of thermokarst ponds. To this end, we installed time-lapse cameras at four different sites in the ADAPT "super-region" during the summer of 2014. These cameras will document the ecological and geomorphological changes that occur around these ponds during the whole year. We also installed a sediment trapping system in one of the ponds (site 'BGR A'). This device will help record the palaeolimnological and sedimentological dynamics within the pond.
- Precipitation samples (rain and snow) were collected at the Centre d'Études Nordiques (CEN) station in Whapmagoostui-Kuujjuarapik as well as from Nunavut Research Institute (NRI) in Iqaluit (Baffin Island), as part of a three-year project that determines the isotopic composition of atmospheric precipitation in the region, throughout 2014–2015.
- On Baffin Island, water samples were collected from different points of Nettilling Lake for reconstruction of the lake water isotopic composition, sediment cores were collected for age-depth model reconstruction and moss samples were collected along the river that brings glacial milk meltwater form Penny Ice Cap to the lake for diatom assemblage study.
- Clay samples were collected along the Foxe Basin beach to study modern foraminifera.
- Submerged living aquatic plants were sampled in order to determine whether or not the lake-DIC and aquatic biota are in equilibrium with the atmospheric $^{14}CO_2$ and to verify that we do not have reservoir effect in our age-depth model.
- On the Milne Ice Shelf, we maintained our oceanographic mooring that has continuously recorded temperature and salinity in Milne Fiord since May 2011. Water samples were collected in both the fiord and from two small streams running into the fiord from Purple Valley. Ice samples were taken from the ice shelf. We measured glacier melt using our network of ablation stakes on the Milne Ice Shelf and Glacier.
- Ice penetrating radar (IPR) surveys of channels and cracks on the Milne Ice Shelf aimed to improve understanding of the shape and structure of these features, while an IPR survey along and across the Milne Glacier improved our understanding of the glacier morphology and grounding line.
- During the annual ArcticNet research cruise we were able to access an ice island in Kane Basin. The ice island ('Petermann Ice Island (PII)-K') was approximately 1 km^2 and was located at 79°N, 71°W at the time of fieldwork on August 5th. We deployed two tracking beacons for drift monitoring and installed stakes with temperature sensors to study surface melt rates. Additionally, an IPR system was towed across the ice island's surface for 1.5 km to measure thickness.
- A grounded ice island near the community of Resolute, Nunavut was visited in August 2014 to conduct a study to determine the influence of this ice mass on the physical, chemical and biological oceanography of the surrounding water column. We measured water salinity, temperature, nutrient concentrations and chlorophyll-a.
- Ice islands and glaciers were photographed to improve our techniques in photogrammetric generation of digital elevation models which will be used to measure mass loss/ deterioration in the future. Using the extensive Radarsat-1 and -2 archive at the Canadian Ice Service, we are recording the drift and deterioration of ice islands from northwest Greenland. A geospatial database is now being created to document these ice

hazards and will be made publicly available when complete.

- The ARCHIVES team completed the sampling of fossil trees in high-boreal and subarctic lakes used to crossdate 10 thousand-year-old reference tree-ring series. These chronologies fill an important gap in data that was revealed in the last IPCC report which documented the amphi-Atlantic millennium-scale climate for three continents excluding North America. Moreover, they were able to map fires on more than 300 km of latitude by relating fire chronology with dendrochronological climate reconstructions. Finally, they completed the instrumental monitoring network for tree growth covering almost 10 degrees of latitude.
- The ARCHIVES group worked on reconstructing the water supply and/or the hydroclimatic variables used to model water supply over the past two centuries at high temporal resolution for the areas where hydroelectricity is produced in northern Quebec. The spatial and temporal variability of the Quebec-Labrador climate was analyzed by i) reconstructing values of climatic variables for the same grid points as those used by climate models, and ii) extending the time-scale studied further back into the last millennium using subfossil trees found in boreal lakes and lake sedimentary sequences.

RESULTS

Tundra ponds and groundwater flows were investigated at Polar Bear Pass (Figure 1). Preliminary analysis of groundwater data (from 2007 to 2010) indicates that groundwater inflow in the post-snowmelt season (month of July) is not an important source of water to tundra ponds (Figure 2). Pond water levels in the summer period respond to rainfall inputs and losses due to evaporation. Groundwater flow from wet meadows increases during wet seasons and declines during warm/dry seasons. During the wet season, groundwater flow is largely dominated by the pattern of rainfall (duration/intensity/amount). In drought periods, the aquifer characteristics (thickness of the water zone, topographic gradient, hydraulic conductivity) define the flow pattern. Pond water budget studies (2007, 2008 and 2009) indicate that in July, groundwater inflows are not important but inputs (rainfall) and losses (evaporation) control pond storage (i.e. water table fluctuations). This occurs whether it is a warm/dry season or a cold/wet season. A PBP digital elevation model (DEM) has been finished thanks to the efforts of Kelly To (undergraduate summer student, McMaster University), and the database of stream/pond temperatures (2007 to 2013) has been finalized. Data analysis of results is ongoing.

Greenhouse gas (GHG) emissions from lakes were investigated in subarctic Québec and on Bylot Island (Figure 3). Despite their shallow depths, lakes in subarctic Québec remain stratified throughout most of the year, with hypoxic or anoxic bottom waters, with the exception of an important fall mixing period. We report extremely high concentrations of both CH_4 and CO_2 in the water column of Quebec palsa lakes, increasing markedly with depth in the southernmost lakes. Strong fluxes to the atmosphere were associated with both diffusion and ebullition, and were greater from the deepest part of the lakes. Ponds on Bylot Island emit significant amounts of greenhouse gases, both through diffusion and ebullition, both emission mechanisms being on average of the same range, but with ebullition reaching larger maximal values, confirming its large spatiotemporal variability. Ice wedge trough ponds are the largest emitters by far as compared to polygonal ponds (on low-center peat polygons) or lakes (thermokarst or kettle). They were estimated to represent 44% of the aquatic area in the sampled valley (glacier C-79) but 92% of total GHG emissions in CO_2-equivalent (not considering ebullition). Trough ponds are potentially even larger emitters during the autumnal overturn as they do stratify for a large fraction of the summer despite their shallow depths. Polygonal ponds emit similar levels of CH_4 as trough ponds, but are CO_2 sinks. Lakes are low emitters of both gases during the stratified

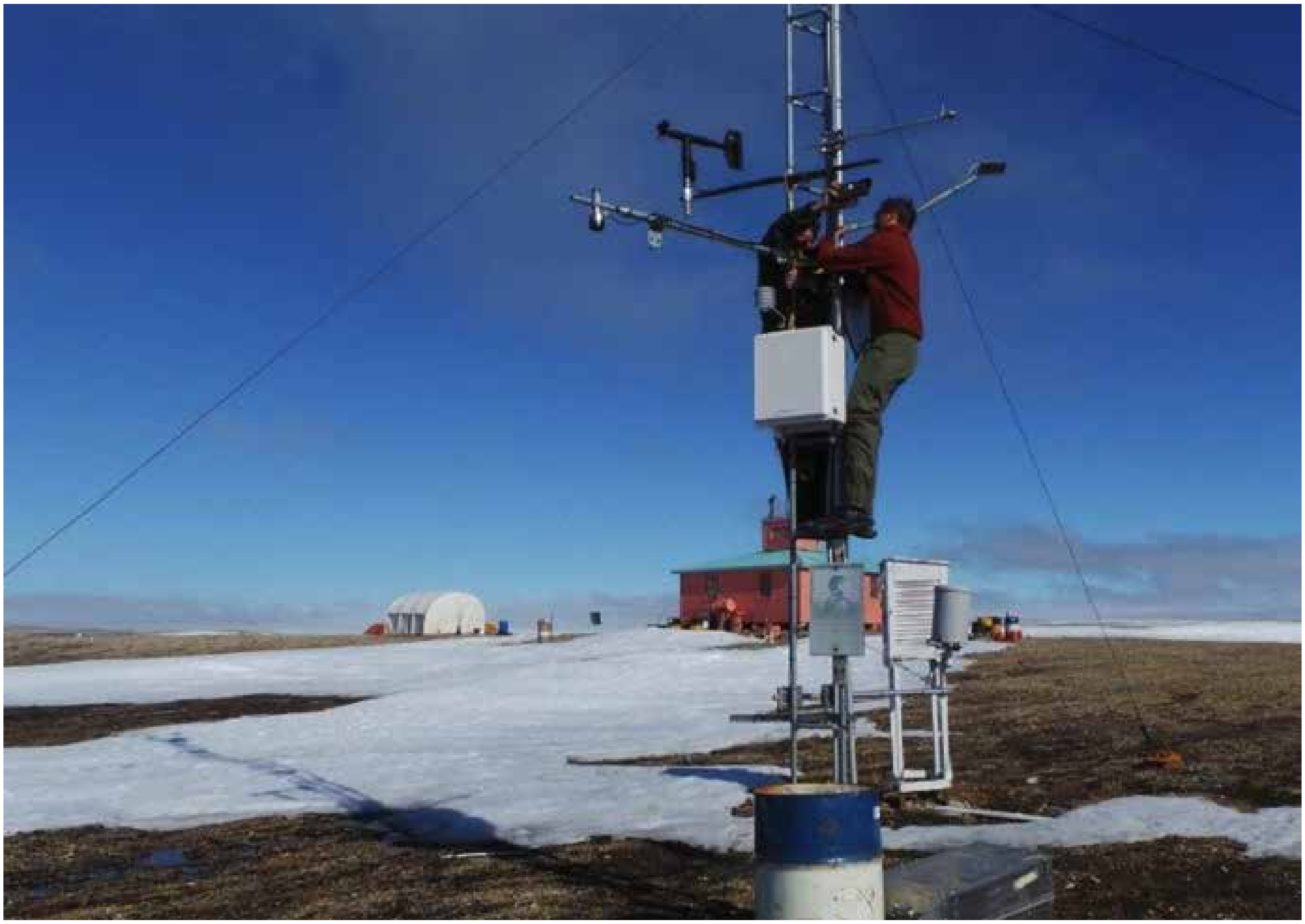

Figure 1. Andy Hamilton, and Adam Fritz (Canadian Wildlife Service; CWS) are re-installing the wetland camera (photo courtesy of Jennie Rausch, CWS, July 1, 2014).

summer period when the epilimnion is well-mixed, but are likely larger emitters during the autumnal overturn, since they store GHG in deep water. While ponds emit relatively young carbon (CH_4 and CO_2) and sometimes century-old CO_2, lakes emit century to millennium-old carbon, particularly at the center of the lake (CH_4 age up to 3500 BP; (Figure 4). A more complete assessment of their GHG footprint, which will consider the amount and age of emitted carbon, is underway.

Preliminary incubation results suggest that lake sediments are a more labile carbon pool than the studied terrestrial sediments (active layer or permafrost), but normalization per unit carbon will be needed to fully validate this trend. The artificial lab conditions did not generate the same results, perhaps owing to a different microbial response under the bottle effect. The patterns in oxygen consumption and GHG production from the different incubation setups are rather complex and point to the need for further experiments where a larger set of lability proxies are measured.

β-diversity of water-column microbes in subarctic Quebec is low among neighboring ponds, and greater among different valleys, associated with greater environmental heterogeneity. Diversity in

Figure 2. Late-lying snowbed is still persisting. In 2012, the snowbed disappeared by this date. Photo shows that there is still some snow/ice in the tundra ponds (courtesy of Jennie Rausch, July 1, 2014).

Figure 3. Sampling CO_2 flux from a permafrost thaw pond.

northern discontinuous permafrost landscapes was driven by stochastic processes, while diversity in southern degraded permafrost landscapes was determined by environmental factors. β-proteobacteria were the dominant group in all thaw ponds, while methanotrophs accounted for up to 27% of the total sequences, indicating the importance of methane as a bacterial energy source in these waters. Oxygenic (cyanobacteria) and anoxygenic (Chlorobi) phototrophs were also well represented, the latter in the low oxygen bottom waters. Community composition appears to be determined by depth and geographic proximity of the ponds, while environmental conditions play an import role. Geomorphology has a strong influence on pond biology and methane release.

Rotifers were an order of magnitude more abundant in subarctic thaw ponds than in nearby rock-based lakes. A high latitude clone of *Daphnia pulex* had a significantly lower food threshold for growth than the temperate, clone implying adaptation to lower food availability even under warmer conditions. The food threshold for growth of the high latitude *Daphnia* was ~ 4 times higher when fed cyanobacterial versus picoeukaryote prey. The effect of lower temperature and poorer prey quality interacted strongly to affect zooplankton fatty acid content and composition.

The ice thickness of the termini of the four largest glaciers flowing into Yelverton Inlet, Ellesmere Island, was measured in July 2014 using a portable ground penetrating radar system. These ice thickness measurements are the first ever for these glaciers, with values from 153.9 m at the northern end of the Inlet to 263.2 m at the southern end (Figure 5). A new high resolution DEM of White Glacier, Axel Heiberg Island, was produced by merging ~1500 oblique photos taken from a helicopter in July 2014. Using the new technique of Structure from Motion, this DEM has a resolution of ~50 cm, and provides information on how the volume of the glacier has changed over the past ~60 years since the first map of the region was produced by Swiss scientists. PhD student Laura Thomson, who is spending a semester on exchange at the World Glacier Monitoring Service in Zurich, Switzerland, in winter 2015, will use this new DEM to update the mass balance record of the glacier. Summer 2013 was unusually cold in the study area, with time-lapse photos from the Petersen and Milne Ice shelves indicating that snow remained for the entire summer at most locations (Figure 6). For the first time in many years, a positive annual mass balance of +45 kg m^{-2} yr^{-1} was measured in 2012–2013 on White Glacier.

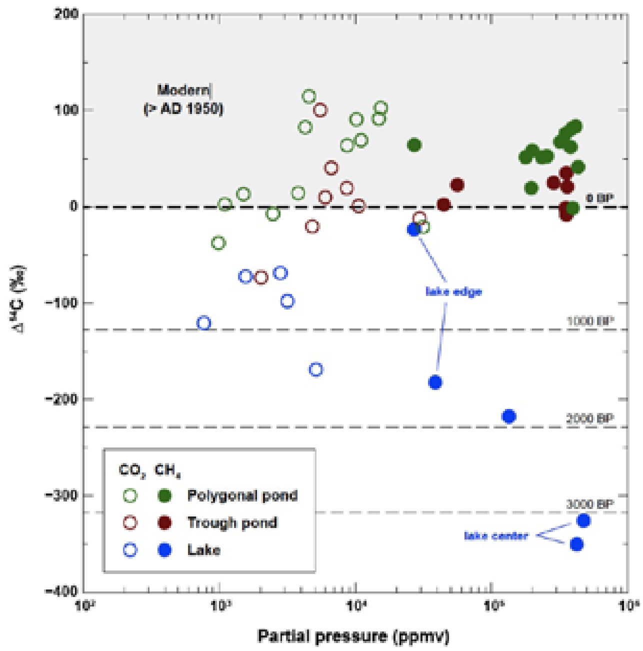

Figure 4. Carbon age (radiocarbon signature $\Delta^{14}C$) in methane and CO_2 plotted against its partial pressure in ebullition samples collected from submerged funnels in a series of lakes and ponds on Bylot Island during summers 2013 and 2014. From Bouchard et al. 2015. © Bouchard, Laurion, Preskienis, Fortier, Xu, Whiticar, 2015.

Temperatures affect the stability of ice shelves. The spring and early summer of 2014 was similar to the same period in 2013. In contrast, the summer of 2012 had five times as many positive degree-days. A profile of conductivity and temperature in the Milne Fiord epishelf lake indicates very little change since the previous summer. An examination of thin sections of ice from the Milne and Petersen ice shelves revealed that bubble size, shape and concentration as well as bulk salinity are the most important variables for determining the SAR backscatter. Ice microtexture and salinity measurements across the central unit of the Milne Ice Shelf showed that this ice was of marine origin.

Preliminary results indicate that phytoplankton biomass adjacent to a grounded ice island near the Resolute community is higher than normal and similar to bloom conditions (Figure 7). Salinity and temperature profiles near the ice island had a staircase pattern that may be indicative of double diffusion. Photogrammetric DEMs of ice islands are a viable technique to measure shape and deterioration (Figure 8); however, work needs to continue to improve protocols (flight pattern, intervalometry, exposure settings and vertical camera setup). The ice island that was visited in Kane Basin (Figure 9) was between 130 and 140 m thick and has drifted approximately 50 km to the east in a broad arc since August. A support vector machine algorithm based on four SAR variables (T22, Krogager double-bounce decomposition, Neumann tau and the second beta angle) was able to discern ice islands from other background ocean types most of the time.

Tree-ring time series and isotopic analysis were used to reconstruct past climatic and hydroclimatic conditions. A network of over 200 tree-ring series spanning the last two centuries was constructed on an area covering the northern part of the boreal forest in Quebec and Labrador (600 000 km^2). A fire history analysis allowed us to demonstrate that the size and frequency of past fires corresponds to the history of droughts for the past two hundred years. We demonstrated that the size of the fires was inversely proportional to the inflow to the LG2 reservoir. Dendrochronology also allowed us to reconstruct key hydroelectric production variables (volume, duration, time of spring flood) over the past 200 years. Based on the use of markers such as wounds (scars) inflicted on riparian trees by floating ice during extreme floods, we reconstructed the volume and amplitude (maximal flow) of past floods. In the LG4 sector, after a dry period between 1850 and 1930, a gradual increase in water yield began in 1930, ending in the 1960s and 1970s, and followed by a gradual decline between 1985 and 2000. At the Caniapiscau reservoir between 1850 and 1900, the water yield appeared to fluctuate at around 1000 m^3 s^{-1}. Subsequent years, between 1900 and 1945, appear to have had low water yields (750–900 m^3 s^{-1}), with little variability from year to year. We have also observed a significant increase in spring runoffs since 1950; they are more variable, but of greater volume (average of 1200 m^3 s^{-1}). We also

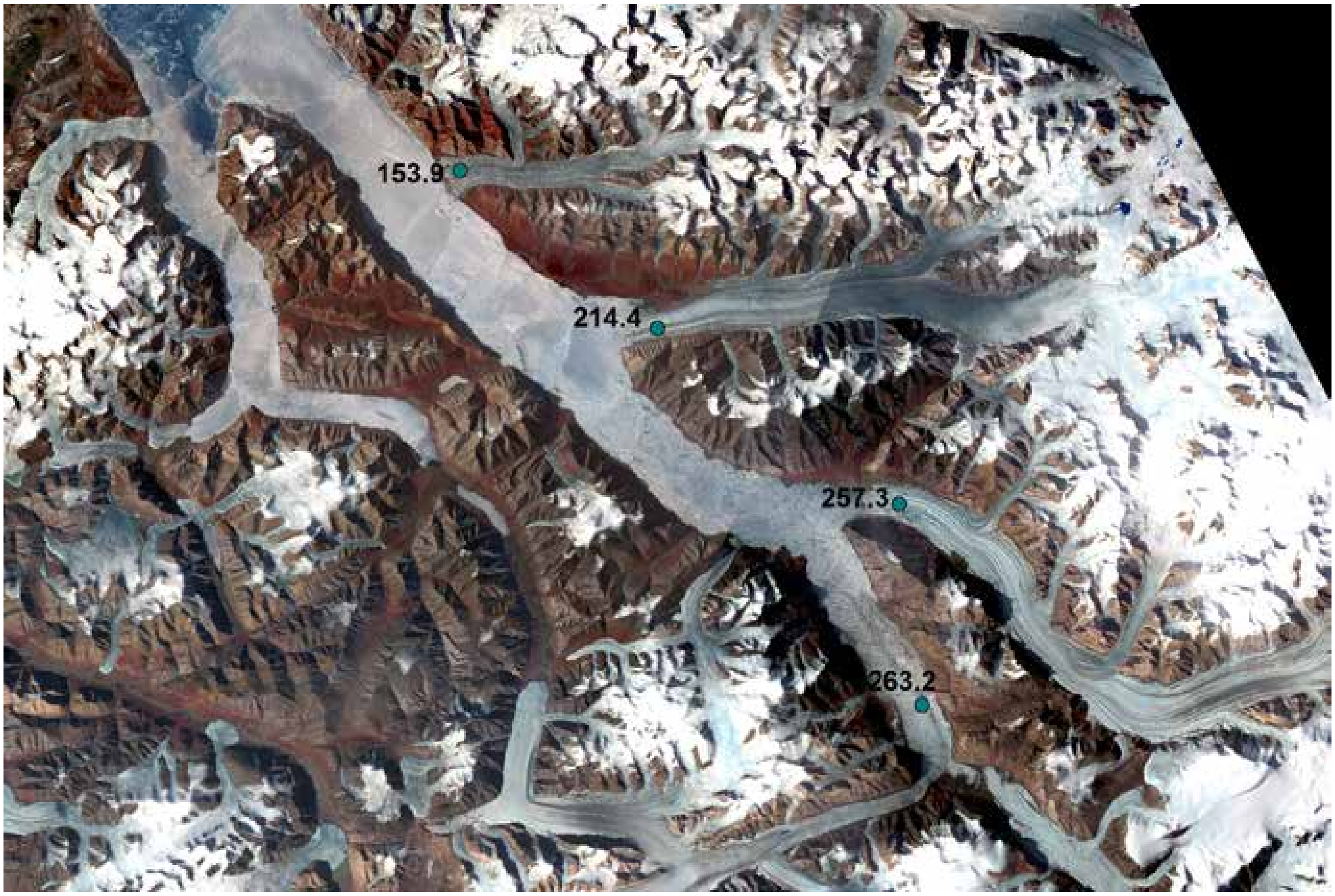

Figure 5. Ice thickness of the termini of glaciers in Yelverton Inlet in July 2014.

demonstrated that spring floods tend to occur earlier in the centre of Quebec/Labrador than in coastal areas.

The isotopic ratios of carbon and oxygen ($\delta^{13}C$ and $\delta^{18}O$) in tree growth rings were analyzed and used to reconstruct the hydro-climatic conditions of the past two centuries. In all, 1799 $\delta^{13}C$ analyses and 1798 $\delta^{18}O$ analyses were conducted. Based on the hydro-climatic parameters that correlated best with the isotopic ratios, we reconstructed the maximum temperatures for the summer months (June to August) and the flows of the large rivers in the area (Ashuanipi, Churchill, and Caniapiscau) for the months of July to November over the past 200 years. Reconstructing flows is essential to understanding the changes in water regimes upstream of the Grande Rivière basin. The reconstructed series revealed sharply contrasting conditions, marked by alternating climate patterns where hot, dry periods followed cold, wet periods. They also made it possible to document specific climate events, such as the cooling that followed the eruption of Mount Tambora in 1815.

We established a network of long tree-ring time series in northern Quebec's boreal sector. In all, 2565 subfossil trunks were recovered in six lakes upstream of the La Grande hydroelectric complex. By cross-dating samples to the calendar scale, we were able to produce six local chronologies covering at least 1238 years and composed of 105–622 subfossil trunks. The temperatures reconstructed based on the six local series do a fairly good job of reproducing the increase in average temperatures observed in July–August over the last century. This is the first

Figure 6. Looking across the Milne Ice Shelf from the temporary camp.

dendroclimatic reconstruction of temperatures from the last millennium in eastern North America. This reconstruction shows that temperatures rose in the 11th and 12th centuries during the Medieval Warm Period (MWP), until a shift toward cooler temperatures then ushered in the beginning of the Little Ice Age (LIA) around 1250. Summer temperatures then remained low and were marked by cold episodes of a few decades. Overall, our data show a striking congruity between the dates of the biggest volcanic eruptions in the past centuries and reduced growth in tree-ring time series. For instance, a few decades of slow growth were observed after the three biggest volcanic eruptions of the last millennium: the eruption of Samalas in 1257, the eruption of Kuwae in 1456, and the double eruption of an unidentified volcano in 1809 and Tambora in 1815.

Finally, a millennial tree-ring isotope series was produced based on living and subfossil trees. Correlation analyses and response functions showed that $\delta^{18}O$ values were more useful than $\delta^{13}C$ for climatic significance and reconstructing maximum summer temperatures. For the first time in northeastern North America, these analyses revealed climate trends throughout the period 997–2006 C.E. Three climatic periods emerge: a warm period (997–1250) attributed to the MWP, a cold period (1450–1880) corresponding to the LIA, and the modern period (1950–2000), which is relatively cold with considerable warming in the last three decades. The reconstructed series also showed that the MWP was the warmest period of the last millennium (0.2°C warmer than the previous century). Moreover, we demonstrated that the cold and warm periods of the last millennium could have been caused

Figure 7. Grounded ice island (about 250 m long) near Resolute Bay, NU on August 29, 2014.

Figure 8. A 3-D model of a 2 km² ice island found in Greendlandic waters created by photogrammetry (structure from motion).

by solar forcing and that the cold period of the LIA corresponded to the period where multiple volcanic episodes (eruption of unknown volcano in 1809 and of Mount Tambora in 1815) occurred at the same time as the Dalton Minimum (Naulier et al., accepted).

With respect to our goal of better understanding of the past and present of subarctic thermokarst ponds, we have analyzed Species–Environment relationships in thermokarst ponds on both sides of the Hudson Bay region (Figure 10). Modern diatom assemblages of 37 thermokarst ponds of Wapusk National Park (Manitoba) were studied in relation to multiple limnological and environmental gradients stretching from the boreal forest to the coast of Hudson Bay (BA student Olivier Jacques, co-supervision with Frédéric Bouchard). Within the ADAPT “Super-Region” (sites SAS, KWK, BGR, NAS) in northern Quebec, MSc student Valentin Proult (co-supervision with W.F. Vincent) completed an analysis of the composition of periphytic diatom communities in 11 thermokarst ponds in relation to substrate types (shoreline vegetation) and multiple limnological and environmental gradients. MSc student Camille Ménard (co-supervision with Frédéric Bouchard) performed a paleolimnological analysis of fossil diatoms preserved in a sediment core from a thermokarst pond (Puddle Pond) near Churchill (Manitoba). Her work revealed assemblage shifts that are likely associated with precipitation changes and widespread lake desiccation observed in the region that can be attributed to low snowmelt runoff (Bouchard et al. 2013; Geophysical Research Letters).

Finally, for the purpose of our multi-year hydro-ecological monitoring of thermokarst lakes and ponds in the James Bay–Hudson Bay region of northern Quebec (PhD student Biljana Narancic, co-supervision with Brent Wolfe), in 2014 we continued our water sampling and limnological profiling of a total of 86 systems located between latitudes 49°15.113’ and 56° 55.423’ N and longitudes 78°02.512’ and 76° 22.750’ W. As part of that study, the relative influence of evaporation, precipitation and permafrost conditions on the hydrologic budget of thermokarst ponds within the ADAPT “Super-Region” will be assessed, using oxygen isotope composition of lake/pond waters from several years and seasons. Preliminary results show that lakes located in sporadic permafrost terrain (KWAK and SAS) experience greater evaporation compared to the lakes in discontinuous permafrost terrain (NAS and BGR) and that accelerated permafrost degradation plays an important role in driving lake hydrologic changes (Figure 11). Our results suggest that thawing permafrost in discontinuous permafrost terrain offsets the effect of evaporation, whereas lakes in sporadic permafrost terrain are most vulnerable to become evaporation-dominated.

Figure 9. PII-K (approximately 0.8 km x 1.2 km) while adrift in Kane Basin on 5 August, 2014.

DISCUSSION

It was surprising to determine that groundwater inflows are not important to the tundra ponds at Polar Bear Pass in the post-snowmelt period (July) in either a warm/dry year or a cool/wet year. Error estimates were low for the pond water budgets in 2008 and 2009 providing confidence in our observations. Still, further work is required to verify this pattern across Polar Bear Pass. Others in the High Arctic have indicated that groundwater inflows are important in the sustainability of ponds and wetland (see Marsh and Woo, 1977; Young and Woo, 2000), suggesting that the local site conditions (geology, slope) are important in assessing groundwater inputs.

The microbial community in subarctic thaw lakes and ponds is responsible for many processes which are significant for climate warming, including anaerobic methane production, and aerobic bacterial decomposition and methanotrophy, depending on environmental conditions. The composition of this community depends in turn upon environmental conditions influenced by climate warming and degradation of permafrost landscapes. The effect of climate change on the abundance of prey organisms, such as picoeukaryotes and cyanobacteria, is expected to have repercussions for the zooplankton that feed on them.

Although summer 2013 was unusually cold, there is no sign of long-term recovery of the Ellesmere Island ice shelves from their rapid breakups which have occurred

Figure 10. Sediment trapping system installed at the 'BGR A' site (ADAPT Super Region), near Umiujaq (Eastern Hudson Bay). An optical trap (center), equipped with a collecting funnel, records sedimentological events throughout the year, while two side 'home-made' traps sample settling material during the same period. Photo: A. Matveev.

since 2005. Over the past decade they have reduced in area by approximately half, from just over 1000 km^2 in 2005, to just over 500 km^2 today. Comparisons of the differences in speckle pattern between pairs of SAR satellite images is enabling measurement of complete regional glacier velocities in the Canadian High Arctic for the first time. These indicate that the majority of iceberg discharge to the oceans occurs through a few very large glaciers. Changes to the dynamics of these glaciers may therefore result in dramatic changes to regional ice fluxes. Work is ongoing to understand the temporal variability of iceberg discharge to the ocean in this region due to factors such as glacier surging.

A large portion of the Milne Ice Shelf is composed of a marine ice type, which had not been previously recognized in the scientific literature. The possibility that basement ice was present at depth in the ice shelf was considered in the past (Jeffries 1985), but our current work presents the first direct evidence for this. In addition, the presence of marine ice at the surface indicates either that meteoric ice types (iced-firn derived from snowfall or glacial ice that has flowed overland) never extensively covered the Central Unit of the ice shelf, or that these ice types were ablated away. Ice islands remain difficult to detect using SAR imagery. The supervised classification scheme that we developed exhibited a moderate degree of confusion between some ice islands and ice rubble/ridges as well

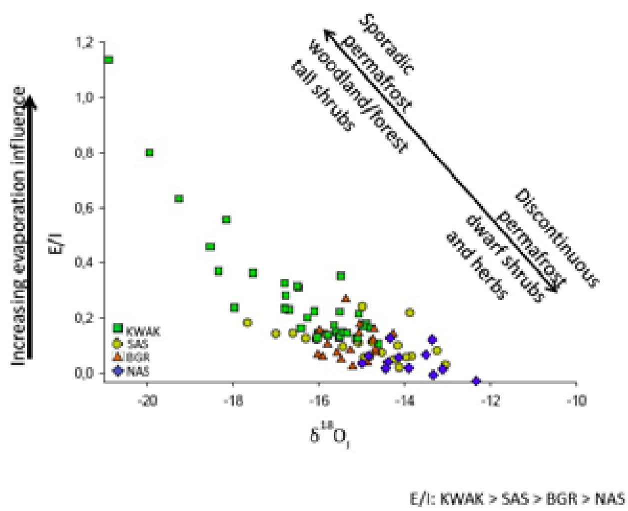

Figure 11. Calculated E/I values versus $\delta^{18}OI$ for 86 lakes sampled in mid-summer of 2013 along an ecoclimatic gradient in northern Québec.

as confusion between other ice islands and first-year ice. This underscores the need for further examination of other SAR variables and a better understanding of confounding variables such as SAR geometry and environmental conditions (snow melt, wind speed, etc.).

ARCHIVES built the first tree-ring time series network making it possible to reconstruct the hydroclimates of the past two centuries (or even the past two millennia for the La Grande complex) in northeastern North America. They made it possible to identify the climatic regimes of the past decades and of the last millennium (recent warming, Little Ice Age, Medieval Warm Period), evaluate the relative importance of the main external climatic forcing mechanisms (orbital, solar, volcanic, anthropogenic), and assess the scope of recent warming in light of the natural variability during the last millennium. This work is already being incorporated into the next hemispheric temperature reconstitutions (2k pages currently being prepared), in which they will help correct the misrepresentation of northeastern North America in the IPCC synthesis reports. ARCHIVES has paved the way for new studies on water flows over the last millennium in northern Quebec. Such studies are of great interest to this project's industrial partner, Hydro-Québec, which is concerned about potential long term droughts that could have an impact on the security of electricity supply in view of climate change.

CONCLUSION

Freshwater environments in the Arctic continue to face climate-related change in the form of permafrost degradation, changes in snowmelt and hydrology, and loss of ice shelves and glacier mass, with important implications for human use of their environments as well as for the ecosystems which depend on them.

The ARCHIVES team's work has helped shed new light on the multi-decadal variability of water yields, primarily in the La Grande sector. They focused on the biggest hydrological event—spring flooding—in the context of intensive operation of a complex of hydroelectric power stations. Spring flooding is the main event that fills hydroelectric reservoirs, and a good understanding of the temporal variability of spring water yields is fundamental to informed power plant management. Temperature reconstructions were another of the project's contributions. ARCHIVES successfully combined the methodological approach of modelers who use current knowledge to forecast upcoming regimes in a context of climate change with that of paleo-environmentalists who reconstruct the past. In both cases, assessing the level of uncertainty is complicated by the dearth and brevity of observations available to calibrate reconstructions and parameterize models. ARCHIVES has made an important step in combining the two approaches.

Thermokarst lakes may be the most abundant freshwater ecosystems types in the circumpolar North. Our results show that they contain complex food webs involving several taxonomic and functional groups of zooplankton, as well as diverse bacteria including methanotrophs.

In spite of a brief hiatus over the past two years, the ice shelves and other cryospheric features along the northern coast of Ellesmere Island will continue to change in the coming decades and are in danger of disappearing entirely. Ice islands adrift in the Arctic Ocean remain poorly understood and should be considered a hazard to navigation and infrastructure. Continued measurements are needed to monitor the evolution of the breakup of sea ice, ice shelves and glaciers across the study region, and the connections between them.

Our new findings at Ward Hunt Island and the observations of ongoing vital change highlight the vital importance of continuing ArcticNet activities at the far northern coast of Nunavut. We intend to continue this work in the exciting new project 'Northern Frontier'.

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HYDRO-ECOLOGICAL RESPONSES OF ARCTIC TUNDRA LAKES TO CLIMATE CHANGE AND LANDSCAPE PERTURBATION

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ABSTRACT

Average annual air temperatures in the Northern Hemisphere have been the warmest 30-year period of the last 800 years (IPCC 2013) and there is growing evidence that the Arctic terrestrial cryosphere is also being significantly altered and is highly susceptible to the effects of a rapidly changing and increasingly variable climate (ACIA 2005; IPCC 2007a,b, 2013; AMAP-SWIPA 2011). Permafrost temperatures have increased in the past few decades, and these increases have been attributed to increased air temperature and changes in the timing and thickness of snowcover (IPCC 2013). While freshwater systems and related hydro-ecological processes are particularly sensitive to changes in climate and related impacts on cryospheric components, the specific nature and the magnitudes of the effects on ecosystem structure and function are not well understood. The occurrence of lake shoreline retrogressive thaw slumping (SRTS) has been increasing in the western Canadian Arctic over the past several decades, as has the incidence of the slumping of steep hillside terrains of fluvial valleys (Kokelj et al. 2013). The goals of this research are to: 1) conduct three integrated landscape-lake process and modeling studies that will improve our regional understanding of the sensitivities/responses of upland tundra lakes to CVC; 2) to develop and validate an integrated landscape-geochemical, lake-ice, hydro-ecological model applicable to cold regions/Arctic systems; 3) to evaluate how changes in atmospheric circulation and related hydro-climatic trends are affecting the spatial distribution of water resources (lentic and lotic) and the occurrence of extreme hydrologic events in high latitude western and northern Canada; and, 4) to develop and test new and innovative automated water quality/hydrometric monitoring systems for application in the Arctic. The project is producing legacy data and products of direct benefit to the development of adaptation options for the conservation, protection and management of arctic freshwater ecosystems to present and future climate variability and change.

KEY MESSAGES

- The Arctic is expected to display a warming that is more than twice the global average, show decreases in snowcover and sea-ice extent, display further retreat of permafrost, glaciers and ice-caps, and have increased inter-annual variability in weather conditions.
- Projected higher surface air temperatures and altered climate regimes are expected to have pronounced effects on the freshwater cryosphere (snow, permafrost and freshwater ice), which in turn will have cascading effects on the hydrology, chemistry and ecology of Arctic lake ecosystems.
- This project has conducted integrated landscape-lake process and modeling studies that have improved our regional understanding of the sensitivities/responses of upland tundra lakes to climate variability and change.
- The project has further developed and validated an integrated landscape-geochemical, lake-ice, hydro-ecological model (MyLake) that is applicable to cold regions/Arctic lake systems.
- The project tested the application of new monitoring technologies (i.e., automated instrumented buoy and mooring system) and has utilized experimental mescocom approaches to assess the effects of changing cryospheric conditions (landscape and aquatic) on geochemistry and ecological structure and function.
- Using lake shoreline permafrost slumping as an indicator of landscape climate change effects, we have found significant differences in lake chemistry, aquatic plant productivity, invertebrate food webs and fish communities between slumped and undisturbed lake catchments in the western Arctic.
- Enhanced understanding has been achieved in terms of understanding the variability and complexities of food web structures in a network of intensively studied upland tundra lakes representing a gradient of landscape disturbance associated with thawing permafrost.
- This project has evaluated how changes in atmospheric circulation and related hydro-climatic trends are affecting the spatial distribution of water resources and the occurrence of extreme hydrologic events in high-latitude western and northern Canada.
- As this project expanded its focus to include a broader range of type and size of lentic and lotic freshwater systems, it provided a more comprehensive understanding of regional characteristics and responses in such systems to a changing climate.
- This project engaged northern communities through community outreach activities, and through the training and hiring of northerners to assist with the field and laboratory work.
- This project has produced legacy data and products of direct benefit to the development of adaptation options for the conservation, protection and management of arctic freshwater ecosystems to present and future climate variability and change.

OBJECTIVES

The strategic research objectives of the project were:

1. to characterize and improve our modelling capability for current and projected lake ice cover (under future climate change scenarios) in a latitudinal gradient and latitudinal distribution of Arctic lake sites;
2. to evaluate how changes in atmospheric circulation and related hydro-climatic trends are affecting the spatial distribution of water resources and the occurrence of extreme hydrologic events in high-latitude western and northern Canada;

3. to develop an improved process-based understanding and modelling capability of the changes in water quality (e.g. temperature, dissolved oxygen, carbon flux) in response to changing lake ice conditions under present and future climate regimes;
4. to improve understanding and modelling capability of the limnological and ecological relationships between aquatic productivity, nutrients, and geochemistry of Arctic lakes across a gradient of landscape perturbations; and
5. to further develop an automated ice buoy and subsurface mooring system for continuous year-round monitoring (in real-time) of weather conditions, lake ice cover (initiation, growth over winter, breakup in spring), light penetration into the lake (through ice in winter), and lake water quality (chemistry, temperature, oxygen levels, dissolved organic carbon). Data collected by this system contributes significantly to objectives 3, and 4 above.

INTRODUCTION

The Arctic has been identified as the region in the Northern Hemisphere that is most susceptible to the effects of climate variability and change (CVC), and is expected to display a warming that is more than twice the global average (3.7ºC for the period 2070-2089), a decrease in diurnal temperature range, a decrease in daily variability of surface air temperature in winter and an increase in daily variability in summers, show decreases in snowcover and sea-ice extent, display further retreat of permafrost, glaciers and ice-caps, and have increased interannual variability in weather conditions (IPCC 2001, 2007a,b, 2013; ACIA 2005; AMAP-SWIPA 2011; AMBIO 2011; ABA 2013). Such significant changes/shifts in climatic regimes are expected to have far-reaching cascading impacts on the hydrology and ecology of northern/Arctic freshwater ecosystems (Wrona et al. 2005, 2006). Freshwater systems are particularly sensitive to CVC because numerous hydro-ecological processes respond to even small changes in the climate regime. Furthermore, hydrological and ecological processes may change either gradually or in an abrupt manner when environmental/ecosystem thresholds are exceeded (AMAP-SWIPA 2011; ABA 2013). A warming climate is expected to directly impact the magnitude and timing of freshwater fluxes to and from lakes and affect a range of physical, chemical and biological processes in the lakes. It is difficult to project the effects changing climate and environmental factors will have on Arctic lakes, partly related to a poor understanding of their interrelationships, and partly related to a paucity of long-term monitoring sites and integrated hydro-ecological research programs in the Arctic.

The lake-rich tundra landscape east of the Mackenzie River Delta, NT, contains aquatic ecosystems that are projected to be impacted by CVC and other environmental stressors (e.g., resource development) in the next few decades. Large-scale permafrost degradation (i.e., increased depth of seasonal active layer and/or landscape slumping) is predicted to increase with the effects of climate warming, along with an enhanced addition of geochemical loadings (e.g., carbon, nitrogen, phosphorus) to the freshwater environment. In addition, changes in the timing and duration of lake-ice characteristics in conjunction with altered geochemical loadings are projected to dramatically affect under-ice and open-water oxygen regimes, 1º and 2º production relationships, and carbon flux.

In light of the need for better understanding of the hydrology and ecology of Arctic tundra lakes, a set of integrated, multidisciplinary hydrological, climatological, and ecological field studies were established under the ArcticNet project "Hydro-ecological Responses of Arctic Tundra Lakes to Climate Change and Landscape Perturbation". The overall objective of this study was to develop a hydro-ecological model for small tundra lakes that can be used to assess the vulnerability of Arctic lake ecosystems to disturbance, such as climate variability/change and those related to development of Canada's northern region. Specifically the research focused on examining the effects of a regionally changing climate and cryosphere (i.e., alterations in landscape permafrost and lake-ice dynamics) on the hydrological, geochemical and ecological (productivity) responses of small, upland Arctic lake systems.

Although the initial focus of this research project was on tundra lakes, the project was expanded to include CVC effects on both tundra lakes and Arctic rivers/streams. As this project continued to expand its focus to include a broader range of type and size of Arctic lentic and lotic freshwater systems, it provided a more comprehensive understanding of regional characteristics and responses in such systems to a changing climate. Additional scientific expertise, via collaborators and graduate students, were utilized to enhance the expanded multidisciplinary scope of the various inter-linked studies.

The research priorities of the project were to: 1) characterize and improve our modelling capability for current and projected lake ice cover (under future climate change scenarios) in a latitudinal gradient and latitudinal distribution of Arctic lake sites; 2) evaluate how changes in atmospheric circulation and related hydro-climatic trends are affecting the spatial distribution of water resources and the occurrence of extreme hydrologic events in high-latitude western and northern Canada; 3) develop an improved process-based understanding and modelling capability of the changes in water quality (e.g. temperature, dissolved oxygen, carbon flux) in response to changing lake ice conditions under present and future climate regimes; 4) improve understanding and modelling capability of the limnological and ecological relationships between aquatic productivity, nutrients, and geochemistry of Arctic lakes across a gradient of landscape perturbations; and, 5) to further develop an automated ice buoy and subsurface mooring system for continuous year-round monitoring (in real-time) of weather conditions, lake ice cover (initiation, growth over winter, breakup in spring), light penetration into the lake (through ice in winter), and lake water quality (chemistry, temperature, oxygen levels, dissolved organic carbon). Data collected by this system contributed significantly to objectives 3 and 4.

ACTIVITIES

Timeframe and study area

Under this project, ongoing fieldwork involved repeated seasonal/annual sampling of a subset of a suite of 60+ tundra upland lakes (ranging from undisturbed to disturbed by permafrost thaw/slumping) located between Inuvik and Tuktoyuktuk in the Mackenzie Upland Region east of the Mackenzie Delta, NT (Figure 1). In 2014, field investigations in the region focused on Noell Lake, and a set of lakes located in the Noell Lake catchment (Figure 2).

As part of our geographical expansion of investigations on Arctic freshwater systems hydrology and ecology (lentic and lotic), in 2014 a fully-automated ice buoy and mooring system was installed in Greiner Lake, located in the central Arctic near Cambridge, NU, to provide monitoring (in real-time) of weather conditions, lake-ice cover (initiation, growth over winter, breakup in spring), light penetration into the lake (through ice in winter), and lake water quality (chemistry, temperature, oxygen levels). In addition, baseline information on water quality and biology was collected from nearby lake/river complexes (lakes and their inter-connecting streams along a topographic gradient) in the Cambridge Bay area.

The inception and development of a lake modelling and monitoring network (Prowse et al. 2009) was used for a sixth year of in-depth, field-based studies over the 2014 spring period. The network covered a latitudinal gradient from temperate southern regions to the far northern Arctic. Field-based measurements were completed at the following sites which fall within ArcticNet IRIS Regions: Noell Lake, Inuvik, NT

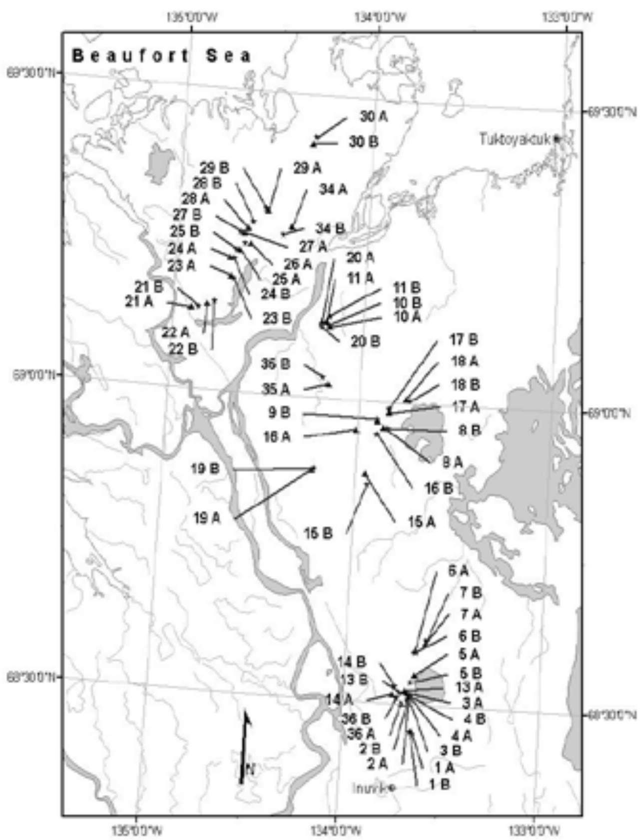

Figure 1. Map showing transect of 66+ study lakes in the Mackenzie Upland Region.

Figure 2. Study lakes in the Noell Lake catchment sampled in 2014 for monitoring potential effects of tundra burns on lake geochemistry. Lakes 3B, 4B and 5B are affected by shoreline slumping; Lakes 5A, NSCL-3, NSCL-11 and NSCL-13 are unaffected by shoreline slumping; Lakes B1, B2 and B3 are located in the burnt tundra area and are unaffected by shoreline slumping.

(IRIS 1: Western and Central Arctic), Resolute Lake, Resolute, Cornwallis Island, NU; Color Lake, Axel Heiberg Island, NU; Lake Hazen, Ellesmere Island, NU, and Lower Dumbell Lake, Alert, Ellesmere Island, NT (IRIS 2: Eastern Arctic) and Ramsay Lake, Churchill, Manitoba (IRIS 3: Hudson Bay). An additional site included in the network is Knob Lake, Schefferville, PQ (IRIS 4: Eastern Subarctic).

Research

Field work, historical data analyses and modelling simulations were carried out as part of the following research activities:

1. Characterization and modelling the hydrological and geochemical linkages between the contributing landscape and the tundra lake water quantity and quality (Peters, Wrona, Prowse, Kokejl, Hille, Moquin, di Cenzo)

This research component has focused on two shallow tundra lakes located in the Mackenzie Upland Region northeast of Inuvik, one affected by shoreline retrogressive thaw slumping (Lake 5B) and one not affected (Lake 5A) which acts as a control lake (Figure 1). The two study watersheds were examined as part of a 60+ lake transect extending from near Inuvik to Richardson Island near Tuktoyaktuk, NT. All the fieldwork and laboratory data analyses for this work were completed in 2012. Interpretation of the data is now completed, as part of an MSc thesis (E. Hille successfully completed her MSc program in December 2014), and three manuscripts for journal publication from this research are now in preparation. Activities are as follows:

- To look at the potential effects of tundra burn scars (resulting from lightning strikes) near some of our tundra study lakes for which we have a considerable time-series of water geochemistry, biological and ecological information, a small network of tundra lakes (comparable in size, contributing landscape, etc.) in the Noell Lake catchment (including slumped, unslumped, and lakes in the newly burned tundra area) were sampled for water quality/geochemistry/biology. The lakes included in this investigation are shown in Figure 2.
- Due to unsafe environmental conditions in late April/early May 2014, we were not able to sample the Noell catchment study lakes prior to ice breakup.
- In early July (after ice-off), and again in August during the period of peak productivity, the Noell catchment study lakes were sampled for core water quality parameters (pH, temperature, DO, conductivity), chlorophyll-a, zooplankton, and water clarity measurements.
- Also, during August, Lakes 5A and 5B were instrumented with a vertical array of HOBO temperature loggers at 1 m intervals, and with YSI water quality sondes (for temperature, pH, dissolved oxygen, specific conductivity and oxidation-reduction potential), while removing those that were deployed the previous year. The instrumentation was installed to freeze in over winter to provide us a second detailed time-series of information on these small tundra lakes from the time of peak productivity (late August) through freeze-up, and under the winter ice cover until spring break-up and the return of the open water season.
- Water chemistry analyses were completed at Environment Canada National Laboratories for Environmental Testing and included: major ion concentrations; dissolved inorganic and organic carbon concentrations; total and dissolved phosphorus and phosphate concentrations; total dissolved nitrogen, nitrate/nitrite, and ammonia concentrations; and pH, conductivity, hardness, and alkalinity measurements.
- Figure 2. Study lakes in the Noell Lake catchment sampled in 2014 for monitoring potential effects of tundra burns on lake geochemistry. Lakes 3B, 4B and 5B are affected by shoreline slumping; Lakes 5A, NSCL-3, NSCL-11 and NSCL-13 are unaffected by shoreline slumping; Lakes B1, B2 and B3 are located in the burnt tundra area and are unaffected by shoreline slumping.

2. Modelling current and projected hydroclimatology, hydrology, river ice, lake ice and related limnological conditions in Arctic rivers and lakes (Prowse, de Rham, Dibike, Ahmed, Bawden, Linton, Newton, Barrett)

- Continued field validations for modelled lake-ice composition at 13 study lakes (along a latitudinal temperature and precipitation gradient) in late winter when the ice thickness was at its maximum. However, due to weather and resultant unsafe environmental conditions, pre-melt ice surveys on Noell Lake (for ice thickness, ice physical properties), also used for comparison with measurements made by the ASL ice-profiler (part of the automated buoy and subsurface mooring system), were not possible.
- Continued expanded lake modelling and monitoring network (including lake sites in Sweden, Norway, Finland, and Russia) to enhance our broader understanding and modelling capability.
- An ice-buoy and instrumented mooring system (developed in collaboration with AXYS Technologies) was deployed into Greiner Lake, located near Cambridge Bay, NU, to provide monitoring (in real-time) of weather conditions, lake-ice cover (initiation, growth over winter, breakup in spring), light penetration into the lake (through ice in winter), and lake water quality (chemistry, temperature, oxygen levels).

- Investigations on the spatial and temporal variation in the spring freshet of major circumpolar Arctic river systems.
- Analysis of spatial and temporal trends and patterns in runoff in cold-regions/Arctic rivers (northwestern Canada).
- Spatial and temporal analysis of hydroclimatic variables affecting streamflow in northwestern Canada.
- Four journal articles were published in 2014 on hydroclimatic drivers and analysis of spatial and temporal trends and patterns in runoff in northwestern Canada.
- Under this research thematic, in 2014-15, two graduate students successfully completed their MSc programs at the University of Victoria (H. Linton, April 2014; R. Ahmed, February 2015).

3. Assessing and modelling changes in food-web structure and productivity of tundra lake systems to present and future climate regimes (Wrona, McCauley, Paquette-Struger, Moquin, di Cenzo, Prowse)

- In August 2014, water quality information (pH, DO, Cond, colour, DOC/DIC and suite of ions) and isotopic (^{18}O, ^{2}H, ^{13}C DIC) parameters; and benthic and pelagic biological samples (e.g., benthic macroinvertebrates, zookplankton, fish, periphyton) were collected from a suite of lakes, and their inter-connecting streams, along a topographic gradient near Cambridge Bay. This will provide crucial preliminary baseline information related to food-web structure and productivity of the tundra lake systems for future investigations (proposed for the next Phase of ArcticNet) on the role that lake ice plays on water quality and food webs.
- Also, during August, a relatively deep lake (>30 m) was instrumented with a vertical array of HOBO temperature and DO loggers at 1 m intervals. The instrumentation was installed to freeze in over winter to provide us a detailed time-series of information on this small but deep tundra lake from the time of peak productivity (late August) through freeze-up, and under the winter ice cover until spring break-up and the return of the open water season.
- Water chemistry analyses were completed at Environment Canada National Laboratories for Environmental Testing and included: major ion concentrations; dissolved inorganic and organic carbon concentrations; total and dissolved phosphorus and phosphate concentrations; total dissolved nitrogen, nitrate/nitrite, and ammonia concentrations; and pH, conductivity, hardness, and alkalinity measurements.
- Continued investigation/assessment of the limnological relationships between aquatic productivity, nutrients, and geochemistry across a gradient of lakes within the circumpolar Arctic in the context of a changing cryosphere.
- Continued data mining aquatic productivity information for circumpolar Arctic lakes (all ≥60°N; numerous lakes with multi-year data), increasing our dataset to ~725 lakes.
- A journal paper on the responses of benthic invertebrate communities to shoreline retrogressive thaw slumps in Arctic upland tundra lakes has been published, another manuscript has been accepted for publication, and two more manuscripts are in preparation.
- B. Paquette-Struger (MSc student, UVic) is expected to complete his Masters degree in April 2015, after which additional manuscripts for journal publication from this research thematic will be forthcoming.

4. Developing a Unique Legacy Database of Freshwater Geochemistry, Biodiversity and Related Environmental Information on Arctic Tundra Lakes

- All the data collected and analysed under the activities summarized above are being archived and will contribute to a unique legacy database and will provide critical baseline information of the current state of arctic tundra lake/river systems.

RESULTS

1. Characterization and modelling the hydrological and geochemical linkages between the contributing landscape and the tundra lake water quantity and quality

Hydrological and Geochemical Responses of Tundra Upland Lakes to Landscape Perturbation

All the fieldwork and laboratory data analyses were completed in 2012 as part of an MSc project (E. Hille; UVic). Ms. Hille successfully completed her MSc program in December 2014. The purpose of this research component was to investigate the hydrological and geochemical linkages between the contributing landscape and shallow tundra lakes in the upland region north-east of Inuvik for catchments both affected and not affected by Shoreline Retrogressive Thermokarst Slumping (SRTS). The specific objectives were to: (i) examine key hydroclimatic drivers of the small tundra lake water balance to assess how historical climate variability and change and the presence of SRTS affects the hydrology of small tundra lake catchments; and (ii) examine the geochemical signature of catchment runoff to and from small tundra lakes to assess the impacts of runoff from the contributing catchment, including terrain affected by SRTS, on the geochemistry of small tundra lakes.

The results of this research demonstrate that the primary factors controlling the water balance and geochemistry of small tundra lakes are ice formation and ablation, the addition of snowmelt water in spring, snow and ice damming the outlet channel, evaporation, summer rainfall events, lake drainage, and SRTS. Figures 3a and 3b show the 2009 Lake Level (LL) of the two primary study lakes, Lake 5A and Lake 5B, from before spring breakup to the onset of fall freeze-up, along with variables affecting LL. Figures 4a and 4b show the concentrations of Ca^{2+}, Cl^{-}, K^{+}, Na^{+}, Mg^{2+} and SO_4^{2-} in the lake water, lake inflow, slumpflow, and lake outflow at Lakes 5A and 5B over the 2008 and 2009 study years. The hydrology and geochemistry of the study lakes exhibited strong seasonal variability:

- The lake levels increased slightly over the ice-covered months, due to the growing weight of the overlying snow. In addition to LL, the concentrations of major ions (Ca^{2+}, Cl^{-}, K^{+}, Mg^{2+}, Na^{+}, and SO_4^{2-}) and TP also increased over the winter months, due to particle exclusion associated with ice formation. As lake-ice forms, the solutes that are initially held in surface water are excluded, increasing the ionic concentration of lake water (Hobbie, 1980; Lesack et al., 1991). The mean concentration of major ions in Lake 5A and Lake 5B was significantly higher ($p<0.05$) in late-winter than during the spring melt and open water periods.
- The addition of snowmelt water from the contributing landscape in early spring led to a rapid rise in LL that was enhanced by snow and ice damming the outlet channel. Notably, the annual peak LL occurred during the early stages of spring snowmelt. During the later stages of spring snowmelt, lake water had carved a trench through the snow/ice dam in the outlet channel, initiating lake drainage and a rapid decline in LL. Meanwhile, the concentration of major ions in the two primary study lakes decreased substantially, due to the addition of relatively dilute runoff water.
- In contrast with the general trends observed in major ion concentrations, the concentration of TP in the two primary study lakes increased at the beginning of spring snowmelt, due to the addition of relatively nutrient rich runoff water from the contributing lake catchment. As spring snowmelt progressed, the concentrations of TP in both landscape runoff and lake water decreased. Overall, the mean concentration of TP in Lake 5A and Lake 5B was significantly ($p<0.05$) higher

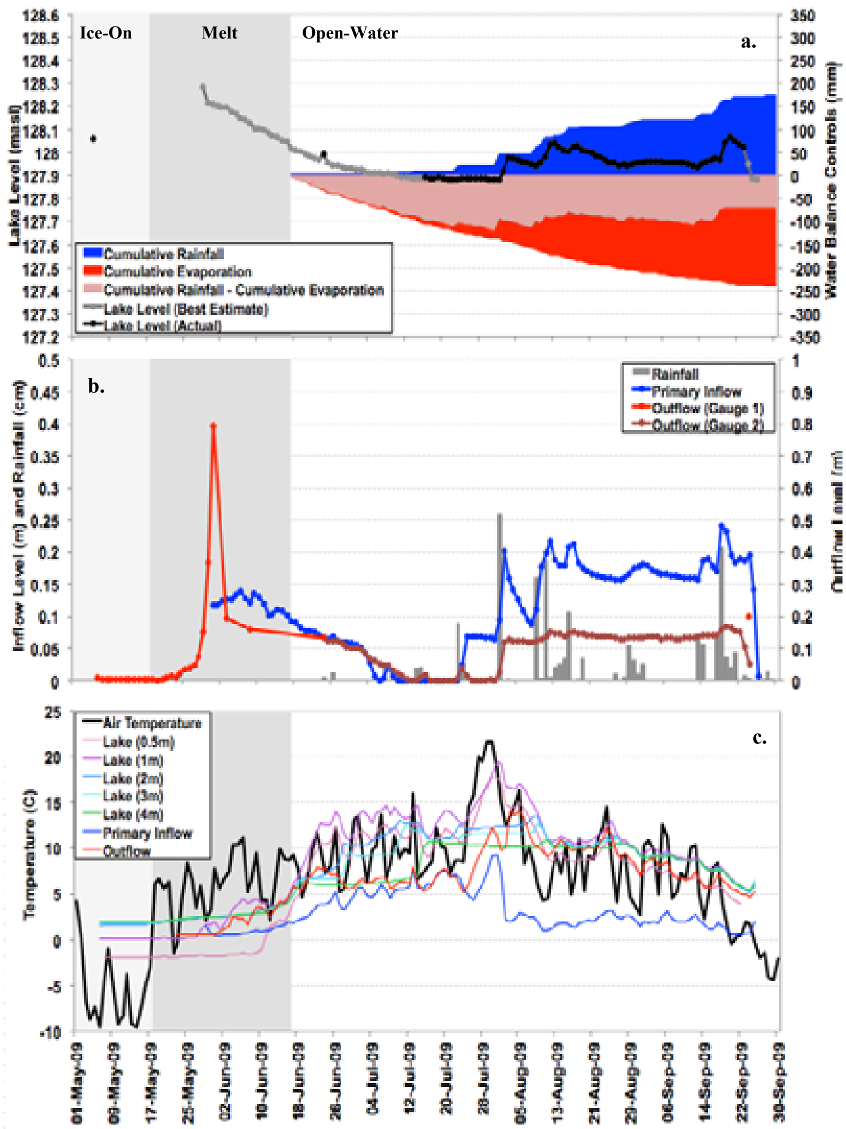

Figure 3a. (a) The Lake Level of Lake 5A from May 1st to September 30th, 2009, plotted with Cumulative Rainfall, Cumulative Evaporation, and Cumulative Rainfall - Cumulative Evaporation; (b) the water level of the Primary Inflow and the Outflow, plotted with Rainfall; (c) Ambient Air Temperature, Lake Water Temperature (at 0.5 m, 1 m, 2 m, 3 m, and 4 m), and the temperature of the Primary Inflow and Outflow.

during the spring melt period than during the ice covered and open-water periods.

- Summer rainfall events were an important source of water recharge for the two primary study lakes. In the absence of summer rainfall events, there was generally a decline in the LL of the two primary study lakes over the open-water period of three study years (2007; 2008; 2009) due to lake drainage and evaporation. In 2007, the LL of the two primary study lakes decreased over the entire open-water period, due to low summer rainfall inputs and high rates of evaporation.

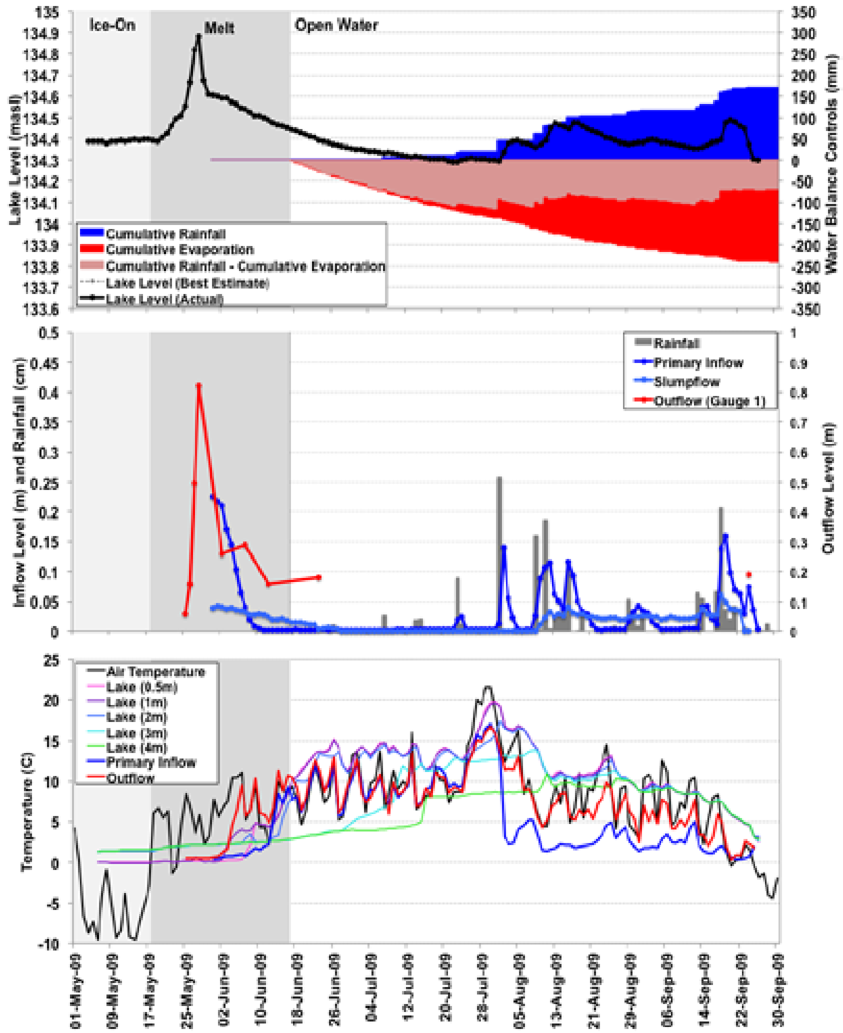

Figure 3b. (a) The Lake Level of Lake 5B from May 1st to September 30th, 2009, plotted with Cumulative Rainfall, Cumulative Evaporation, and Cumulative Rainfall – Cumulative Evaporation; (b) the water level of the Primary Inflow, Slumpflow, and Outflow, plotted with Rainfall; (c) Ambient Air Temperature, Lake Water Temperature (at 0.5 m, 1 m, 2 m, 3 m, and 4 m), and the temperature of the Primary Inflow and Outflow.

By comparison, summer rainfall events were an important source of water recharge to the study lakes in 2008 and 2009, which led to periods of LL rise in July, August, and September.

- In addition to LL, this study revealed that summer rainfall events had a notable effect on lake water chemistry. In the absence of rainfall events, the concentration of major ions typically increased over the summer months. At Lake 5A, summer rainfall events led to a decrease in the concentration of Ca^{2+}, Cl^{-}, Na^{+}, and K^{+}, and an increase in the concentration of Mg^{2+} and SO_4. By comparison, summer rainfall events led to increases in all major ions in Lake 5B. These results demonstrate that summer rainfall events facilitate the leaching of major ions out of slump material.

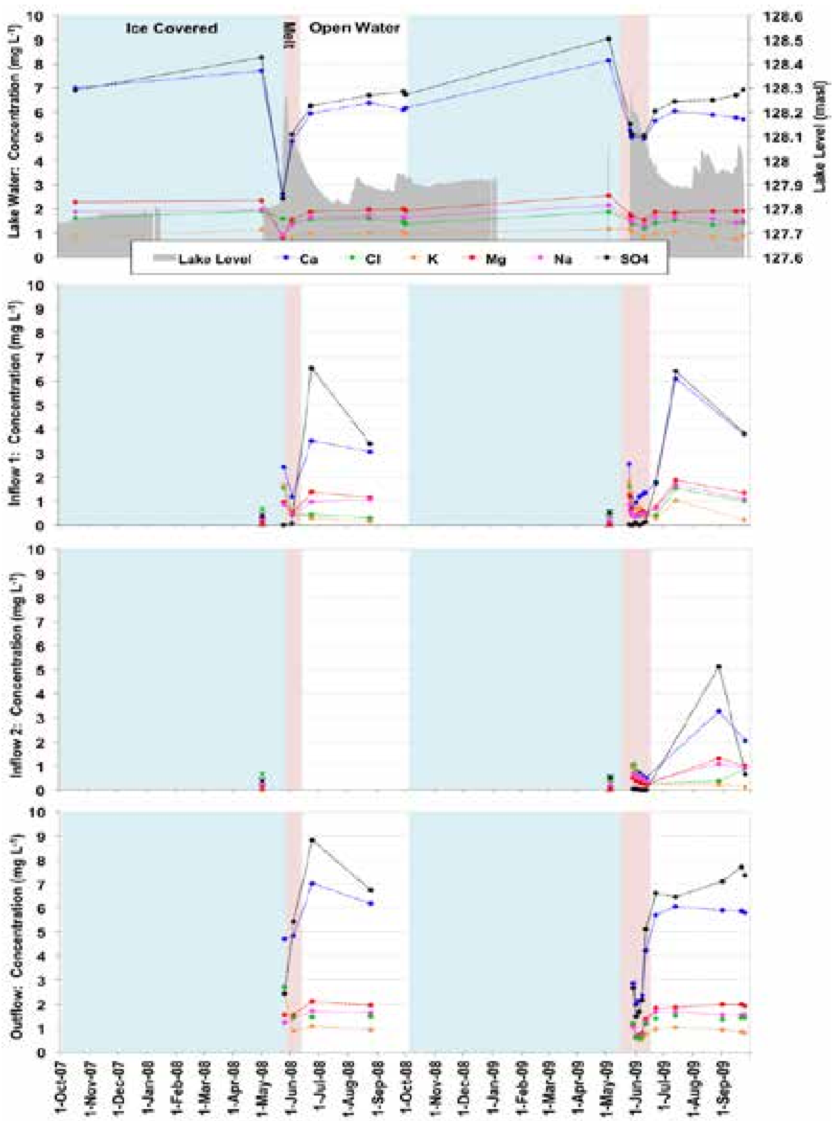

Figure 4a. The concentrations of Ca^{2+}, Cl^-, K^+, Mg^{2+}, Na^+, and SO_4^{2-} in the (a) lake water, (b) inflow 1, (c) inflow 2, and (d) outflow at the Lake 5A study catchment over the 2008 and 2009 study years. The dots represent water and the stars represent snow. Also presented here is the corresponding Lake Level.

Other key results from this research include

- Changes in arctic snow cover, associated with climate variability and change, has important implications for the hydrology and geochemistry of small tundra lakes. The annual May 1st snowpack in Tuktoyaktuk increased at a significant ($p<0.05$) rate from 1958 to 2009. This is in agreement with recent climate projections, which indicated that projected climate warming will lead to an increase in snowcover depth and duration for coastal regions of the Arctic, such as Tuktoyaktuk. A larger May 1st snowpack could lead to a greater rise in LL during spring snowmelt for small tundra lakes located at the northern end of the study

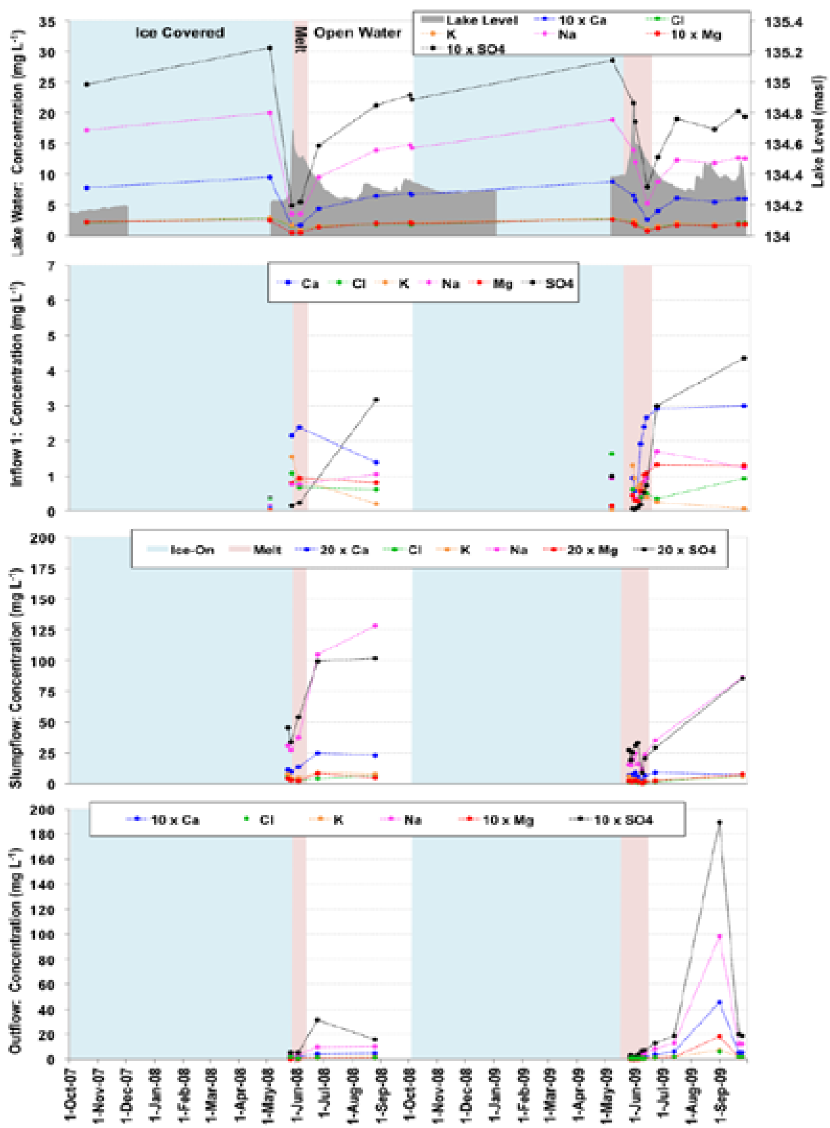

Figure 4b. The concentrations of Ca2+, Cl-, K+, Na+, Mg2+ and SO42- in the (a) lake water, (b) Inflow 1, (c) Slumpflow, and (d) Outflow at the Lake 5B study catchment over the 2008 and 2009 study years. The dots represent water and the solid lines represent snow. Also presented here is the corresponding Lake Level.

region, which could lead to a higher peak LL and more dilution of lake water.

- SRTS increases the snow water equivalent (SWE) in small tundra lake catchments in the study region, as drifting snow collects in the slump scars, increasing total snow storage in the catchment. In 2008 and 2009, the SWE of the SRTS-affected terrain at Lake 5B was 21% and 28% greater, respectively, than the adjacent unaffected terrain, leading to a 2% increase in snowmelt water inputs from the contributing catchment and a 2 cm increase in the LL rise associated with spring snowmelt. Hence, SRTS can result in a greater rise in LL during spring snowmelt, a higher peak LL, and more dilution of lake water.

- There was a significant shift in the timing of the spring freshet and the timing of ice-off in Tuktoyaktuk over the years 1958 to 2009. This is in agreement with other studies, which have shown that climate warming has and will likely continue to lead to earlier spring snow and ice melt initiation for many Arctic regions (AMAP, 2012; Bonsal and Prowse, 2003; Dibike et al., 2012). In contrast with Tuktoyaktuk, there was no statistically significant trend in the timing of spring snowmelt and the timing of ice-off in Inuvik for the same time period. This is in agreement with the work of Lesack et al. (2013), who did not observe any trends in the timing of the spring freshet at the East Branch of the Mackenzie River, at Inuvik. This is not surprising as the effects of recent climate warming are generally amplified in Arctic coastal regions, relative to inland regions, due to the overwhelming effects of declining sea ice extent on ambient air temperature (AMAP, 2012).
- The geochemistry of small tundra lakes in the study region was also driven by SRTS. Major ions leach out of SRTS-affected slump materials in landscape runoff, leading to an increase in the ionic concentration of SRTS-affected lakes. For the two primary study lakes, Lake 5B had higher concentrations of all major ions than Lake 5A, due to the addition of ion rich runoff from the SRTS-affected terrain.
- The lakes in the region are typically interconnected by stream channels as they are situated along a topographic gradient, resulting in a classic “fill and spill” hydrological system described by Spence and Woo (2006). The results of this study indicate that outflows from SRTS-affected lakes could be a source of major ions to downstream receiving lakes, particularly downstream lakes unaffected by SRTS.

The Effect of Tundra Burns on Small Tundra Lake Geochemistry

Field reconnaissance was undertaken in 2013 to identify a set of upland lakes (including unslumped, slumped, and lakes in the tundra burnt landscape) to monitor for effects of the burned area on lake geochemistry. These extensive tundra burns which occurred in June 2012 were the result of lightning strikes associated with convectional precipitation events. Such events are expected to increase with a warming climate—hence, we have a new analogue for a potential effect of a warming climate on tundra lake geochemistry and ecology and a “natural laboratory” to look at these effects. Ten lakes (including three in the burnt tundra area) in the Noell Lake catchment were identified for monitoring (Figure 2), and have now been sampled for water quality seasonally since August 2013. In addition, Lakes 5A and 5B were instrumented with vertical profiling temperature arrays and water quality sondes to collect information on these lakes from the time of peak productivity (late August) through freeze-up, and under ice during winter until spring break-up. Laboratory and field data from this investigation are currently being QA/QC’d and evaluated.

2. Modelling current and projected river ice, lake ice and related limnological conditions in Arctic rivers and lakes

Modelling Current and Projected Lake Ice

Field Validation of Lake Ice Models – the inception and development of a lake modelling and monitoring network (reported as Prowse et al., 2009) was used for a sixth year of in-depth field-based lake ice measurements over the 2014 spring period. This included site visits to 13 lakes along a latitudinal temperature-precipitation gradient from temperate southern regions to the far northern Arctic, along with international locations in Sweden and Alaska. Data collected continue to be used for further development/validation of lake ice and ecology models (including MyLake) for high latitude applications.

Spatial and Temporal Variation in the Hydrology of Northern/Arctic River Systems

The objective of this research was to assess the spatial and temporal variation and trends of key hydrological parameters in northern/Arctic river systems, both in Canada and circumpolar. This research is now completed, and results have been reported in previous ArcticNet reports and at ArcticNet ASMs, as well as in a number of journal publications in 2014. In addition, three MSc theses have been completed at UVic under this research (B. Newton, December 2013; H. Linton, April 2014; R. Ahmed, February 2015), and addition manuscripts for journal publication are in preparation.

Development of an Ice Buoy and Subsurface Smart Mooring System

A major difficulty in monitoring hydro-ecology of lakes in the Arctic is that many locations are very remote, often only accessible by helicopter or float plane. This makes visiting these sites frequently for monitoring purposes very difficult due to the high cost of conducting research in the North. In addition, bad weather in summer and harsh winter conditions interfere with planned field trips to research sites and compromise programs for gathering sets of time-series environmental data. In collaboration with AXYS Technologies (Sidney, BC), we have developed an Arctic Lake Monitoring System (ALMS), a fully-automated Ice Buoy and Subsurface Smart Mooring System, described in detail in previous ArcticNet reports and at ArcticNet ASMs, that comprises a fully-automated ice buoy and subsurface mooring system for continuous year-round monitoring (in real-time) of weather conditions, lake ice cover (initiation, growth over winter, breakup in spring), light penetration into the lake (through ice in winter), and lake water quality (chemistry, temperature, oxygen levels).

Validation and Application of the ALMS – the prototype ALMS was developed and tested over the 2010 to 2012 period in Noell Lake, NT. Described in last year's ArcticNet report, and as presented at Arctic Change 2014 (di Cenzo et al. 2014), there were a number of challenges overcome in developing the ALMS to the point where we are now confident that all the technical issues have been addressed through modifications made to the system. As part of an MSc thesis (B. Paquette-Struger), ALMS data obtained during the 2010 to 2012 prototype development period was validated against other data collected from Noell Lake, either data measured by other scientific instrumentation, or with water grab samples collected and sent to laboratories for analyses. It is through this assessment of the ALMS that many of the technical issues with the system were identified. Highlights of this assessment follow.

In evaluating the overall efficacy and utility of using the ALMS to record uninterrupted meaningful physical, chemical, and biological parameters in an Arctic lake over consecutive open-water and under-ice seasons, three main criteria were considered: (1) were the sensors responsible for recording hydro-ecological data continuously functional for a significant length of time (Functionality); (2) were the measurements being recorded by the sensors representative of the entire lake (Spatial Representativeness); and (3) were the values recorded by the sensors representative of the true parameter-values of the lake (Measurement Validity).

Functionality

During the period of prototype development, the majority of the instruments installed on the original ALMS Ice Buoy and Subsurface Smart Mooring components did not adequately record hydro-ecological data continuously (Table 1). Notable exceptions include the cluster of meteorological instrumentation on top of the buoy, as well as the ASL Ice Profiler, which functionally recorded data continuously for an extended period of time, from September 2010 until February 2012. The lower YSI on the Ice Buoy lost functionality f from mid-April 2011 until mid-September 2011. The upper buoy YSI was never functional (it was never installed for use). Regarding the mooring YSI array, YSI-1 and YSI-4 were only functional from mid-September 2011 to mid-February 2012, YSI-2 exhibited two separate periods of functionality: October 2010 through December 2010; as well as mid-September 2011 through mid-February 2012. YSI-3 exhibited two separate periods of functionality: mid-September 2010 through mid-February 2011; and mid-September 2011 through mid-February 2012.

Despite the problematic overall functionality of the ALMS during the prototype development, many physical and limnological parameters were recorded continuously during consecutive winters and open-water seasons, in both the epilimnion and hypolimnion. After various modifications were made to the ALMS during system development to overcome a number of technical issues, the overall functionality of the various ALMS components was achieved.

Spatial Representativeness

To determine how representative ALMS measurements at its deployment location were of Noell Lake in general, ALMS measurements were compared against laboratory analysis of water grab samples collected proximate to the ALMS, and at six other locations on the lake (Figure 5). Core water quality parameters recorded by instruments installed on the ALMS were found to be spatially representative of Noell Lake water quality. Water quality parameters determined from laboratory analyses of water grab samples collected proximate to the ALMS location did not differ significantly from the parameter values of water samples collected at six additional sites around Noell Lake (p-value <0.05). Further, none of the water quality parameters measured by the ALMS were significantly different than those determined by laboratory analysis of the grab samples taken at its deployment location. It appears, that for Noell Lake under current environmental conditions, measurements

Table 1. Summary of instrument activity on the ALMS Ice Buoy and Subsurface Smart Mooring System. Red denotes inactivity and no recorded data for the entire month. Green represents active instruments with recorded data for the entire month. Blue denotes partial instrument activity with data only being recorded for a portion of the month. Yellow indicates months in which the instrument was not available to record data.

	Ice Buoy				Subsurface Smart Mooring				
Month-Year	Meteorol.	Radiat.	YSI Shallow	YSI Deep	YSI 1	YSI 2	YSI 3	YSI 4	Ice Profiler
Sep-10	a	a	X	a	X	X	a	X	a
Oct-10	A	A	X	A	X	A	A	X	A
Nov-10	A	A	X	A	X	A	A	X	A
Dec-10	A	A	X	A	X	A	A	X	A
Jan-11	A	A	X	A	X	X	A	X	A
Feb-11	A	A	X	A	X	X	a	X	A
Mar-11	A	A	X	A	X	X	X	X	A
Apr-11	A	A	X	a	X	X	X	X	A
Jun-11	A	A	X	X	X	X	X	X	A
Jul-11	A	A	X	X	X	X	X	X	--
Aug-11	A	A	X	X	X	X	X	X	--
Sep-11	A	A	X	a	a	a	a	a	A
Oct-11	A	A	X	A	A	A	A	A	A
Nov-11	A	A	X	A	A	A	A	A	A
Dec-11	A	A	X	A	A	A	A	A	A
Jan-12	A	A	X	A	A	A	A	A	A
Feb-12	a	a	X	a	a	a	a	a	a
Mar-12	X	X	X	X	X	X	X	X	X
Apr-12	X	X	X	X	X	X	X	X	X
May-12	X	X	X	X	X	X	X	X	X
Jun-12	X	X	X	X	X	X	X	X	X

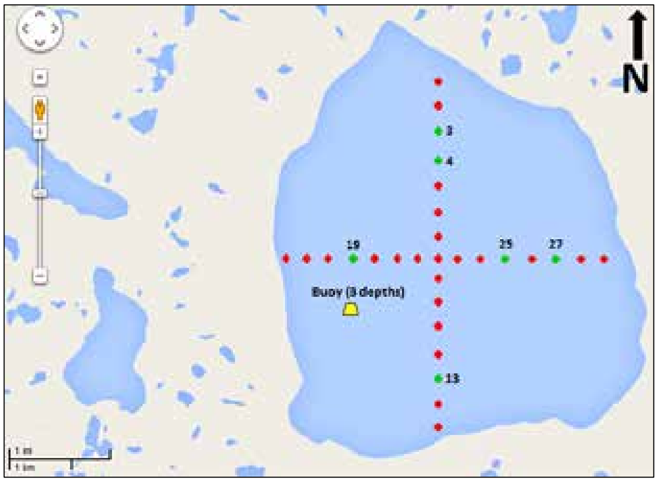

Figure 5. Schematic representation of the Noell Lake ice survey locations (red diamonds) used as water sample locations (green diamonds). Additional water samples were taken at sites proximate to the ALMS (yellow trapezoid).

made by the ALMS at the location it was deployed is generally representative of the overall lake.

Measurement Validation

There was excellent agreement between air temperatures and water temperatures recorded by the buoy and mooring components and those measured using complementary instrumentation (e.g., HOBO loggers; nearby weather stations). However, the agreement was not as strong between YSI-recorded values of pH, turbidity, and specific conductivity, and those determined through laboratory analyses of grab samples. It was not possible to test all the parameters measured by the YSI sondes (e.g. dissolved oxygen, percent saturation of dissolved oxygen, chlorophyll-a, oxidation reduction potential, conductivity, and blue green algae) as there were no corresponding analytic values through which comparisons could be made. Although all YSIs were appropriately calibrated prior to deployment in Noell Lake, their ability to accurately measure and record hydro-ecological parameters over consecutive under-ice and open-water seasons requires further investigation and scrutiny.

The prototype ALMS is now fully developed, free of technical issues, is providing its data series as planned, and is ready to deployed in other Arctic lakes. In August 2014, as part of our geographic expansion in our study area/study lakes, with logistical support from the Canadian High Arctic Research Station (CHARS), an ALMS was deployed into Greiner Lake, located near Cambridge bay, NU.

ALMS time-series data is contributing to our temporal understanding of Arctic lake ecosystems and is assisting in our development of hydro-ecological models for cold regions freshwater systems in the following research areas: landscape hydrology and geochemistry; lake-ice modeling; and aquatic productivity and ecosystem health. These models will be used to assess the vulnerability of Arctic lake ecosystems to disturbance, such as climate variability/change and those related to Canada's and circumpolar northern regions.

Application of the ALMS system is also being considered for a pan-Canadian/pan-Arctic platform for long-term Arctic observing networks such as the pan-Arctic initiative Sustaining Arctic Observing Networks (SAON).

3. Assessing and modelling changes in food-web structure and productivity of tundra lake systems to present and future climate regimes

Responses of Benthic Invertebrate Communities to Shoreline Retrogressive Thaw Slumps in Arctic Upland Tundra Lakes

Permafrost disturbances in the form of shoreline retrogressive thaw slumping (SRTS) which leads to solute-rich terrestrial inputs to Arctic tundra lakes has been shown to change the biological, physical and geochemical properties of affected systems. Documented biological impacts include reductions in phytoplankton standing crop and increased macrophyte abundance as well as changes to the zooplankton and macrophyte community composition. Nine upland tundra lakes in the Inuvik region of the Northwest

Territories, Canada (3 undisturbed lakes; 3 with active slumping; 3 that had active slumping but have now stabilized into inactive slumps) were sampled to assess the effects of SRTS disturbance on benthic invertebrate abundance and community structure. Of the six disturbed lakes, data from one of the lakes was unsuitable for this analysis; hence, this analysis is based on data from 8 of the lakes (5 disturbed, and 3 undisturbed by SRTS).

In last year's ArcticNet report, and at the 2013 ArcticNet ASM, results were presented from our study which examined, using a stratified, mixed-effects experimental design, whether SRTS activity had observable effects on abundance and community composition between undisturbed (U) and disturbed (D) lakes and to further assess whether localized effects in disturbed systems could be discriminated by comparing samples taken adjacent to the thermokarst disturbance (Da) to areas that were more distant (opposite) from the disturbance (Do). Principle Component Analysis (PCA) of benthic macroinvertebrate abundance and composition patterns using sediment chemistry data (Figure 6) revealed the differentiation between U and D lakes was related primarily to increases in the concentrations of calcium in D lake sediments, and to higher organic carbon and organic nitrogen in U lakes. Correspondingly, Chironomidae abundance was found to be significantly negatively correlated with macrophyte standing crop biomass (which is higher in D lakes), while Ostracoda abundance was positively correlated with macrophyte biomass.

Subsequent to results reported last year, further investigation using Redundancy Analyses was undertaken to further examine the effects of sediment physical properties, water chemistry, and macrophytes, to further explain the effects of shoreline retrogressive thermokarst slumping on benthic macroinvertebrate abundance and composition patterns. Results from the RDA follow.

RDA: Sediment Chemistry and Macrophyte Biomass – Data screening procedures led to the removal of total phosphorus, potassium, inorganic phosphorus, iron and organic nitrogen from further analyses. Forward selection with the remaining variables (calcium, magnesium, inorganic carbon, organic carbon, macrophyte biomass) identified magnesium, organic carbon and macrophyte biomass as environmental variables that explained statistically significant levels of total variation in benthic macroinvertebrate community composition. The final RDA model ($F=4.1$, $P<0.001$, 999 permutations) explained 13.5% of the variation (adjusted $R^2=0.10$) in the benthic macroinvertebrate community structure. The eigenvalues of the first two RDA axes were statistically significant: axis 1: ($\lambda 1=0.097$, $P<0.001$, 999 permutations) and axis 2: ($\lambda 2=0.034$, $P=0.022$, 999 permutations) (Figure 7, Table 2). Separation between D and U lakes was primarily along RDA 1, which was loaded positively with gradients in sediment magnesium concentration and associated macrophyte biomass. RDA 2 further separated undisturbed sites

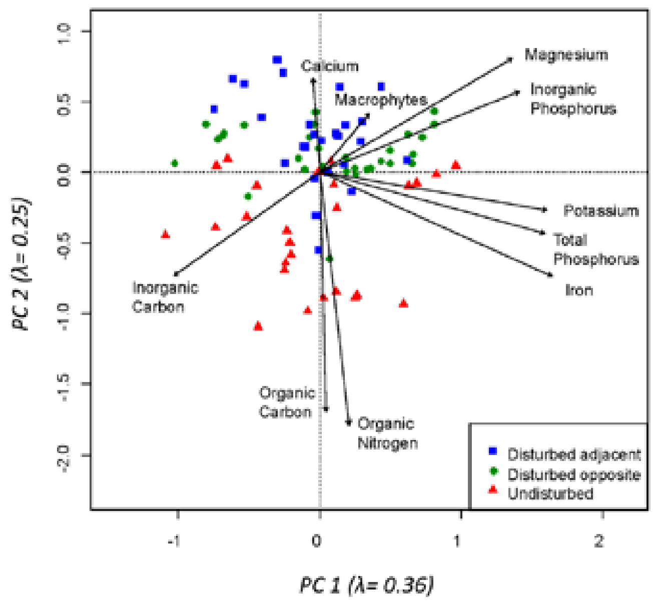

Figure 6. Principal components analysis (PCA) of sediment chemistry and macrophyte biomass from 8 tundra lakes (5 disturbed and 3 undisturbed by shoreline retrogressive thaw slumping) in the Mackenzie Delta uplands region of western Canada. λ represents the proportion of variation explained by the PCA axis.

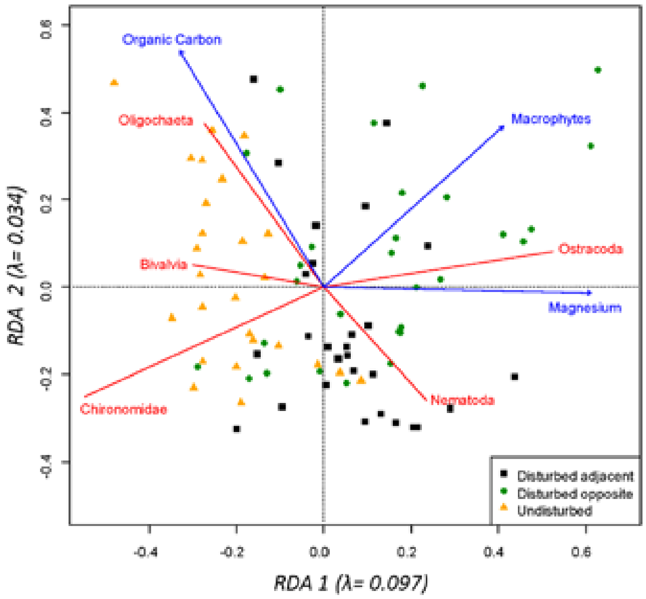

Figure 7. Redundancy analysis (RDA) triplots showing site scores and associated benthic macroinvertebrate species (red lines), and the three environmental variables that independently explain significant amounts of variation, as determined by forward selection, in the benthic macroinvertebrate community patterns of 8 tundra lakes (5 disturbed and 3 undisturbed by shoreline retrogressive thaw slumping) in the Mackenzie Delta uplands region of western Canada. λ represents the proportion of variation explained by the RDA axis.

from adjacent (Da) and opposite areas (Do) within disturbed lakes along organic carbon and associated macrophyte biomass gradients. In general, U and Do sites had higher organic carbon relative to Da sites, while macrophyte biomass was primarily associated with Do sites.

RDA: Water Chemistry and Lake Physical Parameters – Data screening procedures reduced the initial number of water-column chemistry and limnological physical variables to 6 (DOC, conductivity, total phosphorus, alkalinity and magnesium to calcium ratio). Using these 6 variables, forward selection identified DOC as the sole environmental variable in the parsimonious RDA model explaining statistically significant variation in the mean benthic macroinvertebrate abundance. The model (F=10.6, P<0.001, 999

Table 2. Summary results of a redundancy analysis (RDA) of Figure 7 for axes RDA 1 and 2 (a) with loadings of the selected environmental variables for each axis (b).

(a)

	RDA 1	RDA 2
Eigen Value	0.020	0.0073
Proportion explained	0.097	0.034
Cumulative explained	0.097	0.13
P-Value	0.001	0.022

(b)

Environmental Variable	**RDA 1**	**RDA 2**
Magnesium	0.87	-0.020
Organic Carbon	-0.47	0.77
Macrophyte	0.59	0.53

permutations) explained 63.8% of the total variation (adjusted R^2=0.58) in mean benthic macroinvertebrate community abundance. Separation between lake types along RDA1 was apparent with undisturbed lakes tending to have low DOC while disturbed lakes tended to have high DOC.

Geochemical, Biological and Limnological Responses of Arctic Lakes in Relation to a Changing Cryosphere

The overall goal of this research (MSc project, B. Paquette-Struger) was to improve understanding and predictive capability of the limnological relationships between aquatic productivity, nutrients, and geochemistry for Noell Lake, and along a gradient of tundra lakes within the circumpolar Arctic in the context of a changing cryosphere (i.e., alterations in snow accumulation and extent, permafrost and lake-ice conditions).

In order to obtain comprehensive and meaningful baseline information on limnological conditions on Noell Lake for future status and trends assessments, all existing available information (historical and new information collected under this ArcticNet project) was compiled and synthesized. The dataset includes information on the physical characteristics of Noell Lake, characteristics of the Noell Lake watershed and its contributing landscape units, lake bathymetry, local and regional climatology, laboratory analyses of water quality parameters (geochemistry/nutrients), chlorophyll-a, depth-profiling of water temperature and dissolved oxygen levels, fish, macrophytes, phytoplankton, epiphyton and epipelon. Ranges and temporal variability of current chemical, physical, and biological properties of the lake were defined for both open-water and under-ice seasons, in both the epilimnion and hypolimnion, and over successive years. Using the ALMS, continuous measurements were obtained for lake ice, water temperature, conductivity, specific conductivity, percent saturation of dissolved oxygen, concentration of dissolved oxygen, pH, chlorophyll-a, oxidation reduction potential, blue green algae, and total dissolved solids. To complement the information collected by the ALMS, additional information was obtained via an additional array of water quality sensors, in-situ field sampling, and NDS experiments, in order to produce a continuous and comprehensive description of temporal variability (daily; seasonally) to the lake water quality/limnology.

In order to determine the degree of interannual variability in average algal biomass in circumpolar Arctic lakes within latitudinal bands, along a latitudinal gradient, and whether there are any observable trends over the past few decades in response to changing climate and resultant physical and biogeochemical changes in northern aquatic ecosystems, data from a number of sources (academic archives; through personal data requests; and data retrieved from the World Lake Database) on algal biomass, total phosphorous, total nitrogen, dissolved organic carbon, and latitude were compiled, synthesized and evaluated. This dataset compilation includes data collected between 1965-2010 on 727 lakes, representing in more than 1000 lake-years of data.

It is expected that Mr. Paquette-Struger will complete his MSc program in April 2015, and results from this investigation will be finalized by end of this 2014-15 ArcticNet reporting year. Details on the methodology, data analyses, results and interpretation will be available in the thesis from this work. In addition, three manuscripts for journal publication are expected from this project.

DISCUSSION

Over the past 7 years we have been conducting a series of integrated hydrological and ecological field and experimental studies and modelling efforts assessing the effects of atmospheric, landscape and cryospheric (snow and freshwater ice) changes on the hydrology, geochemistry, and ecology of Arctic lakes and rivers. The most significant advances over the period of the project are highlighted below.

Characterization and modelling the hydrological and geochemical linkages between the contributing landscape and the tundra lake water quantity and quality

Integrated hydro-ecological studies have provided new insights into hydrological and geochemical responses of tundra upland lakes to landscape perturbation. In this research component we examined the relative importance of key hydroclimatic drivers of the small tundra lake water balance to assess how historical climate variability and change and the presence of SRTS affects the hydrology of small tundra lake catchments, and quantified the geochemical signature of catchment runoff to and from small tundra lakes to assess the impacts of runoff from the contributing catchment. The study found that the primary hydro-ecological factors controlling the water balance and geochemistry of small tundra lakes are ice formation and ablation, the addition of snowmelt water in spring, snow and ice damming the outlet channel, evaporation, summer rainfall events, lake drainage, and SRTS. Significant progress was made in improving our understanding on the linkages between changes in catchment hydrology and corresponding geochemical responses in upland tundra lakes. The geochemistry of small tundra lakes in the study region was found to be significantly affected by SRTS, since affected lakes exhibit higher concentrations of all major ions compoared to unaffected lakes. The lakes in the region are typically interconnected by stream channels as they are situated along a topographic gradient, resulting in a classic "fill and spill" hydrological system. Consequently, the outflows from SRTS-affected lakes could be a source of major ions to downstream receiving lakes, particularly downstream lakes unaffected by SRTS.

Modelling current and projected river ice, lake ice and related limnological conditions in Arctic rivers and lakes

Analyses of spatial and temporal variation in the spring freshet of major circumpolar Arctic river systems have revealed new insights into the possible climatic and synoptic atmospheric patterns and drivers responsible for observed changes in the spatial and temporal trends in hydrological responses and regional water availability. For example, an increasing trend in Mackenzie-Ob-Lena-Yeniei total spring freshet amounting to about 30 km^3 per decade has been delineated. Furthermore, since the 1980s, freshet pulses tend to be occurring earlier, freshet volumes are increasing, and peak freshet magnitudes are decreasing. Lower freshet volumes from the Mackenzie River were found to be strongly correlated to positive phases of NAO and high ENSO.

Winter snow accumulation in northwestern Canada during 1950-2010 has experienced statistically significant decreases across most of the study basins in most months of the year, while snowmelt over the same period showed increasing trends for January through April, with decreasing trends in May and June. During winter, above average precipitation and below average temperature are associated with a ridge of high pressure over the North Pacific Ocean, advecting cold Arctic air over the study region. Conversely, a ridge of high pressure over the western continent effectively blocks the intrusion of cold Arctic outbreaks, and is associated with above average temperatures and below average precipitation in the study region. Hence, the winter synoptic regime dictates conditions conducive to high or low winter snowpack development, which has profound implications on streamflow in the Mackenzie Basin as snowpack ablation in the mountains is a major source of water contributing to streamflow in the basin. Finally, in general, runoff was found to have increased in most watersheds north of the 60th parallel, especially in the winter, while mid-latitude watersheds generally experienced decreased runoff, implying a northward shift in water availability from adjacent southerly basins.

Information obtained through the annual extensive lake ice surveys, from the ALMS and supplementary instrumentation, information extracted from various databases, and field collections of water quality have led to further development and optimization of lake ice models, which are crucial for projecting future lake ice conditions and resultant effects on under ice environmental conditions.

Assessing and modelling changes in food-web structure and productivity of tundra lake systems to present and future climate regimes

Significant progress was made in enhancing our understanding of SRTS activity affects on the interactions between altered geochemistry, hydrological regimes, and resultant aquatic ecosystem structure and function. The project has provided a new quantitative and mechanistic understanding of how pelagic and benthic autotrophic and heterotrophic production is altered by the addition of thermokarst slump material and the potential cascading implications on aquatic food-webs. SRTS activity was found to reduce phytoplankton standing crop and production (as measure by changes in cholorophyll-a, and to increase macrophyte biomass and species richness. In addition, SRTS disturbance affected both the zooplankton and benthic invertebrate community composition and biomass. Key outcomes of this work have shown that upland tundra lakes in the western Canadian Arctic respond ecologically in a counter-intuitive manner, as compared to temperature lakes in that SRTS lakes having lower water colour and corresponding nutrients, DOC, and pelagic autotrophic production. Moreover, SRTS enhanced benthic heterotrophic production and caused significant shifts in benthic invertebrate communities with Ostracoda and Nematoda becoming dominant taxa in slump affected lakes and compared to Chiromonidae, Oligochaeta and Bivalvia being dominant in unaffected systems.

CONCLUSION

Through an integrated multi-disciplinary approach, this project has provided new knowledge and insights on how climate variability and change affects cold regions/Arctic freshwater hydrology, geochemistry and ecology. Significant progress was made in quantifying the linkages and teleconnections between global, regional and local climate-related drivers and their local and regional effects on hydrological and cryospheric regimes. Through a combination of in-situ experimental studies, synoptic field surveys and modelling exercises, this project identified previously unknown hydro-climatic and hydro-ecological mechanisms, and their inter-relationships, responsible for observed patterns in lake ice, hydrology, water quality and biology under a changing climate at local, regional and circumpolar scales. Our studies reiterated that understanding climate-cryosphere-ecosystem interactions are necessary to predict the future responses and sensitivities of aquatic ecosystems to climate variability and change.

ACKNOWLEDGEMENTS

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SECTION III. INUIT HEALTH, EDUCATION AND ADAPTATION

Section III is composed of ten ArcticNet research projects covering many components of human health and education under adaptation perspectives of climate change and modernization.

INSTABILITY OF COASTAL LANDSCAPES IN ARCTIC COMMUNITIES AND REGIONS

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The submerged sea level lowstand of Cumberland Peninsula, Baffin Island, NU
Robert Deering, Masters Student (Memorial University of Newfoundland)
Nature and triggers of submarine mass failure in coastal waters of southeastern Baffin Island, Nunavut
Ben Misiuk, Masters Student (Memorial University of Newfoundland)
Mapping Clam Habitat in the Arctic: Baseline Data for Fisheries Assessment and Management
Melissa Karine Ward, Masters Student (McGill University)
Geomorphology of hypersaline springs in the Canadian High Arctic
Laura Eerkes-Medrano, Post-Doctoral Fellow (University of Victoria)
Michael Fritz, Post-Doctoral Fellow (Alfred Wegener Institute Foundation for Polar and Marine Research)
Boris Radosavljevic, Post-Doctoral Fellow (Alfred Wegener Institute Foundation for Polar and Marine Research)
Claire Crowley, Research Associate (University of Saskatchewan)
Neil Ednie, Research Associate (McGill University)
Cassandra Lee, Research Associate (Memorial University of Newfoundland)
Sandrine Baillon, Technical Staff (Memorial University of Newfoundland)
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Northern HQP

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Rosie Audlakiak, Northern Research Staff (Community of Qikiqtarjuaq)
Alex Flaherty, Northern Research Staff (Fisheries and Sealing Division, Department of Environment)
Janelle Kennedy, Northern Research Staff (Fisheries and Sealing Division, Department of Environment)
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Geela Kooneelusie, Northern Research Staff (Hamlet of Qikiqtarjuaq)

ABSTRACT

Future climate scenarios and impacts modeling predict changes in climate variables that may increase coastal landscape instability and hazard risk. Projecting the future response of the coastal land system to these changes in climate forcing is a prerequisite for an effective adaptation strategy and forms the core of this ArcticNet project. Through improved understanding of changes in climate, sea level, sea ice, storms and wave climate, seasonal thaw depths, and other aspects of environmental forcing we will assess integrated impacts on coastal landscape stability, including flooding, erosion, habitat integrity, and community vulnerability. Together with northern communities and partners we plan to integrate local and external research and knowledge on climate-change trends and impacts in order to provide a common basis for decision-making at all levels, thereby enhancing community adaptive capacity. Ultimately the goal is to promote informed choices of adaptation measures and enhanced resilience in northern coastal communities.

KEY MESSAGES

Circumpolar Arctic Coastal Communities Observatory Network (CACCON)

- CACCON is a pan-Arctic network of community-engaged, multifaceted, and integrative coastal community observatories. It was initiated over the past year with ArcticNet support.
- The objectives of CACCON include detecting and characterizing Arctic coastal change and acquiring and sharing knowledge for managing change and fostering sustainable outcomes.
- CACCON responds to key issues identified in the State of the Arctic Coast 2010 report (Forbes, 2011), including the observation that "many Arctic coastal communities are experiencing vulnerabilities to decreased or less reliable sea ice, greater wave energy, changing sea levels, changes in winds and storm patterns, storm-surge flooding or coastal erosion, with impacts on travel, subsistence hunting, cultural resources, and housing and infrastructure in communities."
- CACCON is founded on the premise that co-designed and co-produced knowledge in the hands of decision-makers is the key to successful adaptation, sustainable development, and resilient communities. This knowledge has to be built on data that enable an integrated (holistic) understanding of northern coastal social-ecological systems and their stakeholders.
- CACCON will bring together stakeholders, decision-makers, and partners such as Nordregio and ELOKA to facilitate co-design of research agendas and co-production of local knowledge to provide the information needed by local and regional decision-makers. The network will build capacity through sharing insights between stakeholder peers across the circumpolar world to identify priority information requirements for transformational development.
- CACCON will inform and support local and regional decision-making and adaptation planning – and feed back into the network to further prioritize research agendas.

Coastal Community Climate

- Communications with the Northern Transport Company Ltd. in Hay River NWT produced a dataset for the types of weather problems that limit transport operations. These were focused on problems associated with low-visibility, but also included information on the nature and frequency of other problematic events, such as drought-induced wildfire or low water level along the Mackenzie River main stem.
- Low-visibility occurrences exhibit a diurnal pattern, whereby low-visibility events are more likely to occur in the early- to late-afternoon. Stations situated beside large water-bodies observe more frequent occurrences of low-visibility.
- Regional patterns show that the eastern Arctic exhibits relatively more low-visibility occurrences in May-September, whereas the interior region and southern Baffin/ northern Ungava observe most frequent occurrences in the winter.

Community Hazard Mapping

- A report giving sea-level projections to 2100 for Canada, including Arctic communities, was released (James et al., 2014). The projections are based on the recently released Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) (IPCC, 2013) and on Global Positioning System (GPS) measurements of vertical crustal motion.
- There is substantial geographic variability in projected sea-level change through the Canadian

Arctic arising in main part because of the differences in vertical land motion. Projected sea-level changes in the Arctic range from more than 1 m of sea-level fall where the land is rising quickly to nearly 1 m of sea-level rise where the land is sinking at slow rates.

- New glacial isostatic adjustment modelling incorporates recent advances in the understanding of the history of the Innuitian ice sheet and provides an improved fit to relative sea-level measurements and a small number of Global Positioning System measurements of crustal uplift (Simon, 2014; Simon et al., 2015). The revised model provides nearly 30% more water to the global sea-level budget than the Innuitian portion of the previous ICE-5G model.
- Results from participatory mapping workshops in Rigolet and Makkovik, Nunatsiavut (Labrador), indicate that community members actively utilize the land, sea, and ice within municipal boundaries. This is important because these areas provide quality and meaning of life to residents, especially those who may not be able to travel extensively on the land and ice, such as elders.
- Information gathered in participatory mapping workshops in Rigolet and Makkovik complement geotechnical data, and are used to identify areas within the municipal boundaries that community members would like to see protected from development.
- The geohazard datasets compiled for Hopedale, Nunatsiavut (Labrador), assisted community planners in the development of the updated Hopedale community plan.
- Coasts of the Yukon and mainland Northwest Territories in the Beaufort Sea are highly dynamic, in part due to large volumes of ground ice in the region, and are among the most sensitive coasts in Canada to future effects of climate change.

Community Marine Habitat Mapping

- The presence and abundance of rhodoliths in the shallow water habitats (< 50 m depth) of Arctic Bay NU and in Broughton Channel near the community of Qikiqtarjuaq NU is a notable contribution to our knowledge of the diversity of benthic habitats in the Canadian Arctic Archipelago (CAA). The hard substrates associated with these calcareous algae are some of the most under-represented habitats examined in benthic surveys conducted within the CAA. Epifauna consisting of actinian anemones, crinoid and ophiuroid echinoderms, soft corals, bryozoans, chitons, and limpets have been recorded in the samples recovered from these hard substrates.
- Marine habitat mapping of Broughton Channel, near Qikiqtarjuaq, NU, on Baffin Island was further expanded to four new areas near the community. These show varying abundance of clam species, where sandy sheltered substrates claim the highest abundance.
- A partnership has developed with the Government of Nunavut Fisheries and Sealing Division to formulate a commercial harvesting plan for a small-scale clam fishery in Qikiqtarjuaq NU, to be fulfilled over the next three years.

Community Safe Navigation and Anchorage

- The first mapped transit corridor through Beare Sound was recently created, allowing vessels to cut inside Loks Land, eastern Baffin Island NU.
- Expanded new shipping corridors through Anderson Channel and added anchorages and inshore transit corridor around Cumberland Peninsula, Baffin Island, NU.
- Multibeam mapping along northeastern Cumberland Peninsula, Baffin Island,

discovered a Holocene submerged delta 28 m below present sea level in outer Padle Fiord, further confirming the submergence trend across the peninsula.

- Multibeam mapping surveys have uncovered a total of eight submerged deltas, one submerged boulder barricade and one sill platform, which provide sea level evidence for the Holocene submergence trend across northeastern Cumberland Peninsula, NU.
- The project has evolved to focus on key knowledge gaps identified in the State of the Arctic Coast 2010 report. These include more robust projections of local sea-level change in Arctic communities, better understanding of the effects of a changing sea-ice regime on Arctic coasts, more detailed studies of Arctic storms and changing storm climatology, consideration of the fate of Arctic deltas and intertidal systems under changing sea level, wave energy and development pressures, and renewed efforts to develop integrated monitoring strategies in the context of a circumpolar Arctic Coastal Communities Observatory Network.

OBJECTIVES

- To improve understanding of changes in climate, sea levels, sea ice, storms and wave climate, seasonal thaw, permafrost and ground ice, and other aspects of environmental forcing as a basis for assessing integrated impacts on coastal landscape stability, including flooding, erosion, thermokarst activity, habitat degradation and community vulnerability, particularly in areas of high sensitivity and cultural significance.
- To improve our understanding of the effects of changes in climate on Arctic coastal environments, particularly pertaining to coastal and landscape instability, other natural hazards, and community vulnerability.
- To work with stakeholders in the Inuvialuit Settlement Region, Nunavut, and Nunatsiavut to develop improved adaptive management strategies to address changes in both physical and human systems and support sustainable development of safe and healthy communities.
- To integrate local and external research and knowledge on climate-change trends and impacts in order to provide a common basis for decision-making at all levels, thereby enhancing community adaptive capacity. Ultimately, the goal is to support and promote informed choices of adaptation measures and enhanced resilience in northern coastal communities.

INTRODUCTION

Northern communities and community lands, generally located on permafrost in coastal environments, are exposed to a harsh climate, with strong seasonal contrasts in temperature, wind, precipitation, and ice conditions. Under a constant climate, seasonal changes in the landscape and extreme weather events create instability and hazards, including flooding, landslides, thaw failure and subsidence, coastal ice push, storm surges, and coastal erosion. Emerging evidence of climate change in the north and a growing global consensus point to significant changes leading to more severe environmental hazards in the future.

Coastal landscape change in the Arctic has been ongoing for thousands of years and human adaptation has been a constant imperative for Inuit occupying this region. The evolution of Inuit culture is a clear demonstration of adaptation to extreme climatic conditions, but limits to adaptation are seen in the demise of the Thule culture and early European agrarian settlement in Greenland, both due at least in part to climate cooling. The former occupation of parts of the northern Canadian Arctic Archipelago that were later abandoned, as well as early paleo-Eskimo expansion southward to Newfoundland, demonstrates a capacity on the part of northern people to adapt in the past through migration, taking advantage of opportunities to access resources or withdrawing if resources became scarce. More recently, as people have become more dependent on community services available only through hamlets and larger settlements, moving is no longer an acceptable response to environmental change.

The Inuit lifestyle is closely tied to marine resources. Long experience on the land and coastal ocean has allowed the development of traditional knowledge of the physical environment and living resources in a region, as well as an understanding of the range of climate variability expected over timescales of a few generations. This knowledge base provided an understanding of safe practices or routes, such as areas of reliable ice, or of particular environmental hazards. Over the past few decades, and particularly in recent years, the extent of climate variability and change has begun to challenge the limits of traditional knowledge. At the same time, climate change is forcing adjustments in building and infrastructure engineering practices in communities and driving recognition of the need for adaptation at all levels from individuals to communities, regions, and territorial governments. It is expected that the pace of change will increase in the future, with some of the earliest and most severe changes occurring at high latitudes. The greatest warming in recent decades has occurred in the western Arctic, while climate warming has been slower to occur and less clear in Nunavut, Nunavik, and Labrador. However, there is now widespread evidence across the Canadian Arctic for climate warming affecting glaciers and ice caps, vegetation and other living resources, permafrost and seasonal depth of thaw, slope stability, coastal sea-ice conditions, wave energy, sea level and coastal flooding and erosion hazards, among other factors posing increased risk to northern coastal communities and habitats.

Virtually all Inuvialuit, Nunavut, Nunavik, and Nunatsiavut communities are coastal and many emerging resource developments are either located on the coast or, more commonly, require shipping access with coastal implications. Thus coastal infrastructure is a critical issue for northern governments and communities (Ford et al., 2010). The emerging evidence for climate warming in the Arctic is pointing to changes already apparent in coastal ice extent, form, and safety as a hunting platform, sea-level changes, increased wave action and erosion even in communities with rapid uplift and falling relative sea levels, and changes in species composition with implications for coastal habitat integrity and communities dependent on country food. There is a high demand on the part of communities and territorial governments for information on these emerging issues (Catto and Parewick, 2008). The objectives of this project include the acquisition and appropriate consultative distribution of scientific information to support adaptation efforts.

ACTIVITIES

Circumpolar Observatory Network

- The Circumpolar Arctic Coastal Communities Observatory Network (CACCON) was launched with support from IASC, LOICZ (Future Earth – Coasts), and other partners at an initiating workshop in Copenhagen, April 2014 (CACCON, 2014; Forbes et al., 2014c) [NIs Forbes & Bell with HQP Riedlsperger and other partners].
- Submitted funding proposals to Belmont Forum (July 2014) and ArcticNet (October 2014) [NIs Bell & Forbes with CACCON partners including Rasmussen (Nordregio)].
- Contributed to initiating workshop for ArcticSTAR at Columbia University in New York as a result of Future Earth Fast Track Initiative funding for a consortium including CACCON [NIs Forbes & Bell with partners].

Coastal Community Climate

- Activities related to fog and other low-visibility occurrences included investigation of the physical processes causing low visibility in the specific context of the Canadian North. Weather station data were analyzed to develop climatologies of fog and low-visibility occurrence, including detailed breakdown of low-visibility events by type (e.g. snow, fog, mist), region, and time during the day and over the year (e.g. Figures 2-3) [NI Atkinson and HQP Khalilian].
- Once again, a quasi-daily report on the progress of breakup in the Mackenzie Delta, Beaufort Sea, and Amundsen Gulf was issued during the 2014 breakup season, co-sponsored by Natural Resources Canada and ArcticNet. In total 38 reports were provided to a mailing list of more than 300 between May 1 and July 11, 2014. This was the 9th year of the breakup report (Forbes et al., 2014d) and work began on compilation for open file publication [NI Forbes and collaborators Whalen and Fraser].
- Published analysis of climate forcing and trends in the timing of breakup and peak spring flood levels in the Mackenzie Delta at Inuvik (Lesack et al., 2014) [NI Forbes with partners].
- Coastal field observations at Iqaluit, including wind, wave, and current meter data and harbour water properties, were published in an open file report (Hatcher et al., 2014) [NI Forbes, HQP Hatcher, and collaborator Manson].

Community Hazard Mapping

- Work progressed on finalizing sea-level projections and an open file report was released in late 2014 (James et al., 2014b). A presentation on sea-level projections was given at Coastal Zone Canada (James et al., 2014b) and sea-level projections are provided for selected communities in a Canada-Nunavut Geoscience Office 2013 summary of activities (Couture et al., 2014). [NIs James & Forbes with partners].
- Karen Simon completed her Ph.D. dissertation on glacial isostatic adjustment modelling of the Laurentide and Innuitian ice sheets (Simon, 2014). Results focusing on the west coast of Hudson Bay were published (Simon et al., 2014a) and a paper describing a new model for the Innuitian ice sheet is in revision (Simon et al., 2015) [NI James with HQP Simon].
- Eight participatory mapping workshops were conducted in Rigolet and Makkovik, Labrador during August 2014. Using the map-biography approach, community members identified valued spaces and places, including subsistence areas (hunting, trapping, fishing), recreational areas (playgrounds, sites for community festivities), and culturally important areas (graveyards, burial sites), among others [NI Bell and HQP Riedlsperger].
- A field program in Arviat and vicinity, Kivalliq, Nunavut yielded geotechnical data and samples: 60 active-layer soil samples; 59 ground penetrating radar survey lines; 2 near-surface permafrost cores; 18 shore-normal topographic profiles; and community drainage and foundation infrastructure inventories [NI Bell & Forbes with HQP Bagnall and two others].
- Preliminary geohazard mapping in Arviat was published (Forbes et al., 2014a). Working with the Government of Nunavut, productive consultation meetings were held in Arviat with key regional and community planners, local businesses, and local elders over the course of 3 days in August 2014 [NIs Bell & Forbes with HQP Bagnall].
- A permafrost monitoring site following the ADAPT network protocol was installed at Arviat in partnership with the Centre d'Études nordiques (Université Laval), the Government of Nunavut (GN), and the Arviat Wellness Centre [NIs Bell & Forbes with HQP Bagnall and others].

- Geohazard fieldwork was completed during summer of 2014 for the Nunatsiavut communities of Nain, Rigolet, and Makkovik. Work in Hopedale and Postville had been completed the previous year [NI Bell with HQP Lee & Riedlsperger].
- Data were collected for Nunatsiavut coastal geomorphology and composition, infrastructure, community drainage, and surficial ground cover using a high-precision real-time kinematic (RTK) global positioning system (GPS), soil sampling, photographs, and visual observations [NI Bell with HQP Lee & Riedlsperger].
- The geohazard data from 2013 have been transcribed, digitized, and processed to convert them to a format that is compatible within a geographic information system (GIS) while the data from 2014 are in the final stages of processing. These are being added to GIS databases, for use by communities and community planners [NI Bell with HQP Lee & Riedlsperger].
- Rates of shore recession were measured during the time interval 1951-2013 along a 35 km stretch between Komakuk Beach and the Canada-USA border on the Western Yukon Coast (Konopczak et al., 2014). Working with the Geological Survey of Canada (GSC) and the Alfred Wegener Institute, RTK GPS surveys were undertaken at GSC coastal monitoring sites at Komakuk Beach and the border to compute rates for 1991-2012, and other data sources included aerial photographs, SPOT images, and LiDAR surveys in 2012 and 2013 [NIs Forbes & Pollard with collaborators Lantuit (AWI), Couture, Manson].
- Continued annual measurements of slump headwalls of three retrogressive thaw slumps on Herschel Island YT using differential GPS [NI W. Pollard with AWI collaborator Lantuit].
- Collected air and water temperature data and time-lapse imagery from a hyper-saline spring on Axel Heiberg Island, NU, from July 2013-April 2014 [NI Pollard with HQP Ward].

Community Marine Habitat Mapping

- With support from the University of Saskatchewan, completed analysis of bottom camera images from Arctic Bay, NU, while work is in progress on examination of sea bottom videos and the identification of molluscs and echinoderms recovered by grab sampling [NI Aitken with HQP Garner & Crowley].
- Species identifications for polychaetes and crustaceans from Arctic Bay were undertaken by Phillippe Archambault, Université du Québec á Rimouski [NIs Aitken & Edinger].
- With support from GN and CanNor, surveyed marine benthos and sediments in the vicinity of Qikiqtarjuaq NU to examine seafloor habitats in support of an exploratory clam fishery. Data, including 49 camera transects, 46 sediment samples and 74 grab samples from Broughton Channel, were presented in a poster at Arctic Change 2014 [NIs Aitken, Bell & Edinger with HQP Misiuk & Cowan].

Community Safe Navigation and Anchorage

- In partnership with GN, multibeam surveys aboard the MV Nuliajuk mapped uncharted corridors and anchorages in Frobisher Bay, Anderson Channel, Cumberland Peninsula, eastern Baffin Island, including clam habitat in Broughton Channel and vicinity (Hughes Clarke et al., 2015; Mate et al., 2015) [NIs Bell & Forbes with collaborator Hughes Clarke and other partners].
- Multibeam surveys aboard CCGS *Amundsen* covered previously uncharted coastal regions of Baffin Island, including inner reaches of Gibbs Fjord and the region east of Padloping Island [NIs Forbes, Bell, Lajeunesse with HQP Joyal].

- Three piston cores from sea-level lowstand features on Cumberland Peninsula and one from mass transport deposits in Frobisher Bay were acquired aboard CCGS *Amundsen* with support from the GSC. Seven gravity cores from coastal waters of the Cumberland Peninsula were acquired from MV Nuliajuk. Core analysis was undertaken with GSC support at the Bedford Institute of Oceanography in February 2015 and data analysis is in progress [NIs Forbes & Bell with HQP Deering & Cowan and other partners].

Communications at national level

- Communicated findings at Coastal Zone Canada conference in Halifax, Nova Scotia, June 2014 [NIs Bell, Forbes, James with HQP Cowan].
- Presented findings at Geological Society of America conference, Vancouver, British Columbia, October 2014 [NIs Bell, Forbes and HQP Cowan].
- Contributed to IRIS 1 (Western Arctic) report, Chapter 7 on infrastructure (Lamoureux et al., 2015) [NIs Lamoureux, Forbes, Bell, James].
- Contributed to Chapter 2 (Canada's changing coast) and Chapter 5 (Canada's northern coast) of the Canadian Coastal Climate Assessment, for publication in 2016 [NIs Atkinson, Bell, Forbes, James and partners].

Communications at international level

- Communicated research at 8th International Congress of Arctic Social Sciences, Prince George, British Columbia, May 2014 [NI Bell with HQP Riedlsperger].
- Presented results at Arctic Change 2014 international meeting in Ottawa, December 2014, with 19 contributions (11 posters and 8 oral), of which eleven were student presentations [NIs Aitken, Atkinson, Bell, Edinger, Forbes, James & Pollard with most HQP].
- Presented results at the American Geophysical Union Fall Meeting, San Francisco, December 2014 [NI James with HQP Simon].
- Communicated findings at the 11th International Conference on Hydroscience & Engineering, Hamburg, Germany, Sep-Oct 2014 [NIs Forbes & James].
- Presented findings at the Wegener General Assembly, Leeds, UK, September 2014 [NI James with HQP Simon].
- Communicated research at the Arctic in Rapid Transition workshop for ISTAS: Towards Future Research Priorities, Plouzané, France, October 2014 [NI Pollard with HQP Fritz & Tanski].
- Presented at the European Conference on Permafrost, Évora, Portugal, June 2014 [NI Pollard with HQP Fritz & Tanski].
- Communicated findings at the Arctic Biodiversity Congress, Trondheim, Norway, December 2014 [NI Pollard with HQP Becker].
- Presented results at the Arctic-FROST Annual Meeting, Anchorage, Alaska, September 2014 [NI Bell with HQP Riedlsperger].

RESULTS

Circumpolar Observatory Network

Before and following the initiating workshop in April 2014, extensive consultation was undertaken with international and local stakeholders, and potential community partners. By mid-summer, with development of the Belmont Forum proposal, a number of communities had agreed to participate in a network pilot. Discussions were ongoing with the Inuvialuit Settlement Region (ISR) in Canada and pending in the Murmansk region of northwestern Russia. Communities expressing an interest and willingness to be part of a core network included settlements in the Russian Federation (notably Lorino, Chukotka), USA (Shishmaref, Alaska), Canada (Arviat and Clyde River, Nunavut; Nain, Nunatsiavut), Greenland (Kujalleq, South Greenland), and Norway (Unjárgga/ Nesseby, Finnmark) (Figure 1). Special sessions on CACCON were organized at the international Coastal Zone Canada conference in Halifax (June 2014) and the international Arctic Change 2014 meeting in Ottawa (December 2014), with side meetings at the 8th International Congress of Arctic Social Sciences in Prince George (May 2014) and Arctic Change meeting in Ottawa. Representatives from the ISR participated in the Halifax meeting and community members from Shishmaref and Nain attended the side meeting in Ottawa. As an official IASC project for the 3rd International Conference on Arctic Research Planning (ICARP-III) in April 2015, CACCON will have a special session with a discussion panel at that meeting.

Coastal Community Climate

Atmospheric visibility data are sparse in the Canadian North: fewer than 25% of all stations in YK, NT and NU report weather parameters that can be used to analyze visibility (Figure 2). Many stations in Northern Canada do not possess automated weather and visibility observing equipment (e.g., Sachs Harbour), unlike communities in Alaska, which do. This is a great impediment to air travel in Northern Canada. In some cases, aircraft do not go to a community unless a ground observer is calling the visibility and cloud conditions (Sachs Harbour community representatives, pers. comm., 2014).

Project results and analyses of total mean monthly counts of weather occurrences that can reduce visibility show regional patterns. Many coastal stations in the

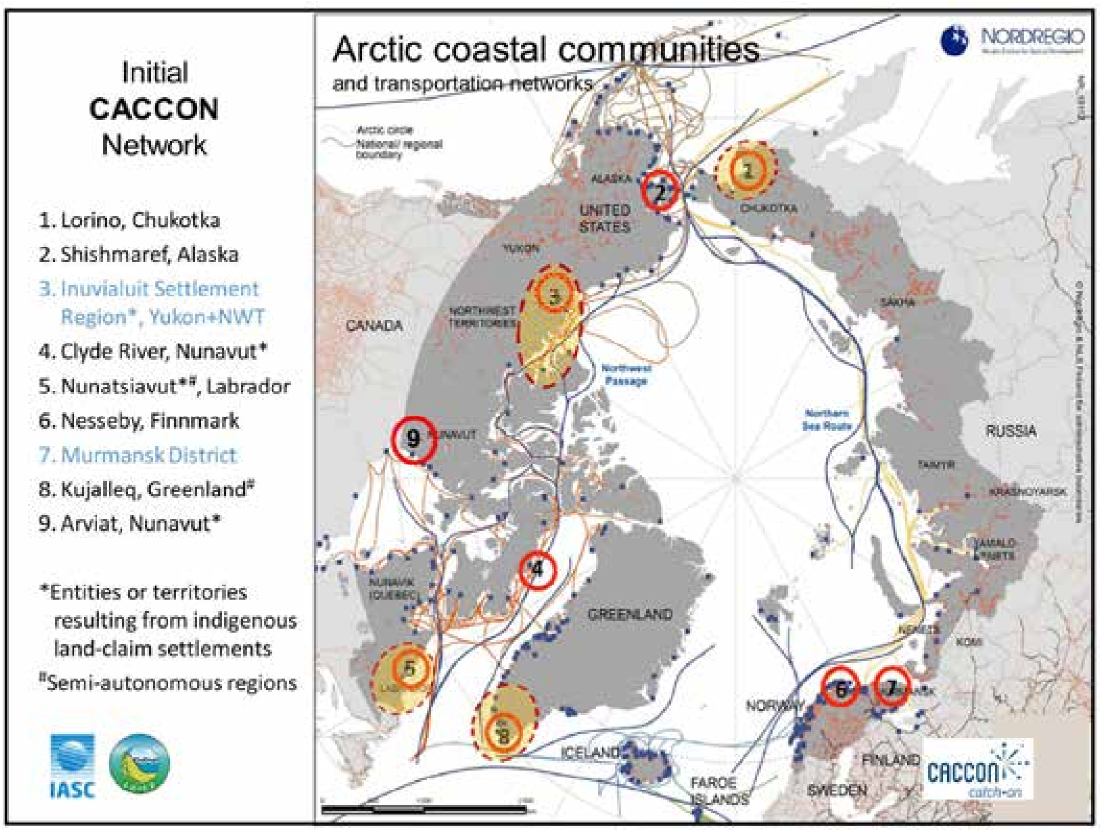

Figure 1. Locations of existing and potential CACCON network hubs, as of July 2014 (Belmont proposal), with potential regional subnets (in yellow). Locations in blue unconfirmed.

Figure 2. Locations of all weather stations that have ever reported data (small yellow dots) and those stations with some data that can be used for visibility and weather studies (large red dots with labels).

Eastern Arctic (Baffin, south Ellesmere) have relatively more frequent occurrences of poor visibility from May - September (e.g. Figure 3). Stations in southern Baffin/ northern Ungava also have more frequent occurrences in the winter, largely dominated by snow (e.g. Figure 4).

The occurrence of low visibility also exhibits a diurnal pattern, whereby its occurrence is favoured in the early- to late-afternoon (Figure 5). This pattern is evident at most locations. Sites near large bodies of water have more frequent total numbers of low visibility occurrences.

Community Hazard Mapping

Sea-level Projections

Sea-level projections were generated for 22 locations in northern Canada (Figure 5). Over this area, vertical crustal motion ranges from nearly 15 mm/yr of uplift at La Grande 1, on James Bay, to about 1 mm/ yr of crustal subsidence on the Beaufort coastline at Tuktoyaktuk, Northwest Territories. The differences of vertical crustal motion lead to profound differences in projected sea-level change (Figure 6). At Tuktoyaktuk, NWT, which is subsiding at about 1 mm/yr, sea level is projected to rise by nearly 1 m by the year 2100 for the RCP8.5 scenario (RCP is Representative Concentration Pathway.) At La Grande 1, Quebec, which is rising at nearly 15 mm/yr, sea level is projected to fall by more than 1 m for RCP2.6. At the two sites rising at a lower rate (Iqaluit and Kugluktuk),

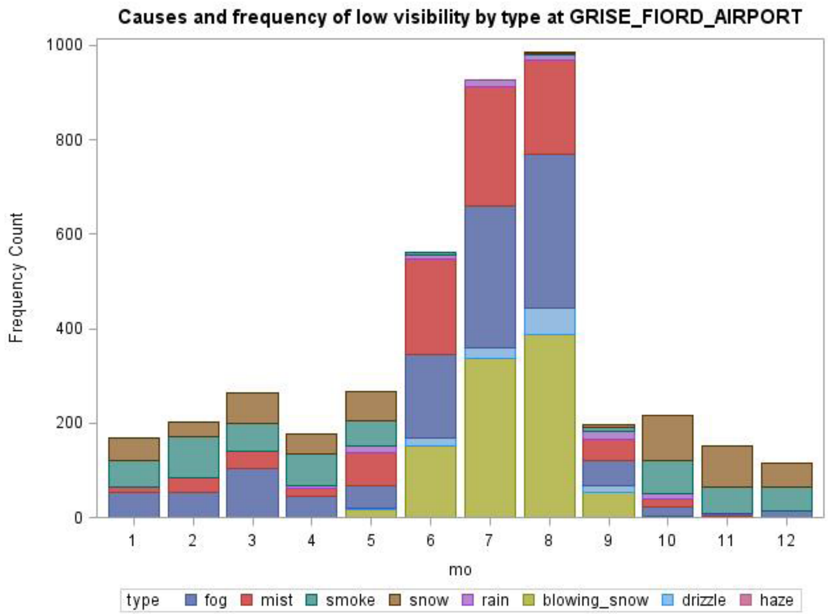

Figure 3. Total counts of weather types for the community of Grise Fiord, NU.

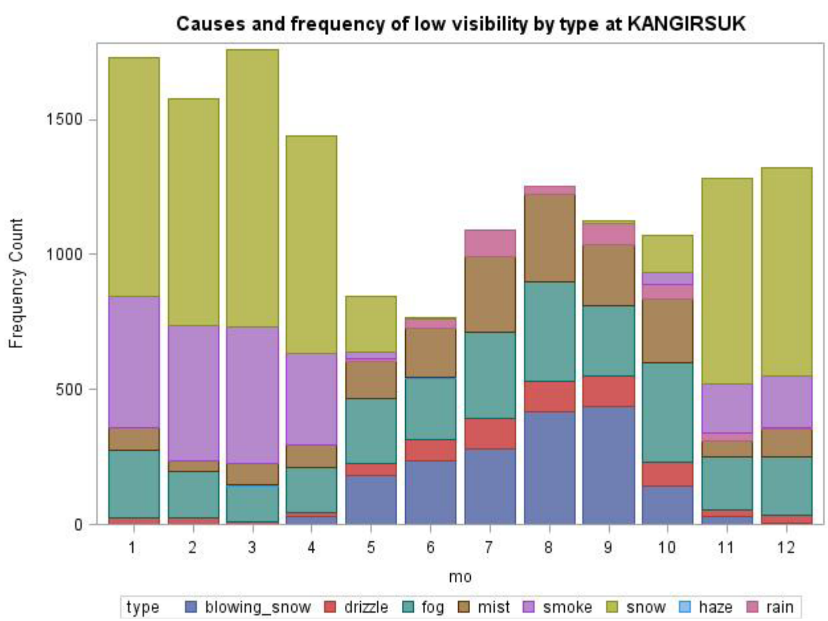

Figure 4. Total counts of weather types for the community of Kangirsuk, QC.

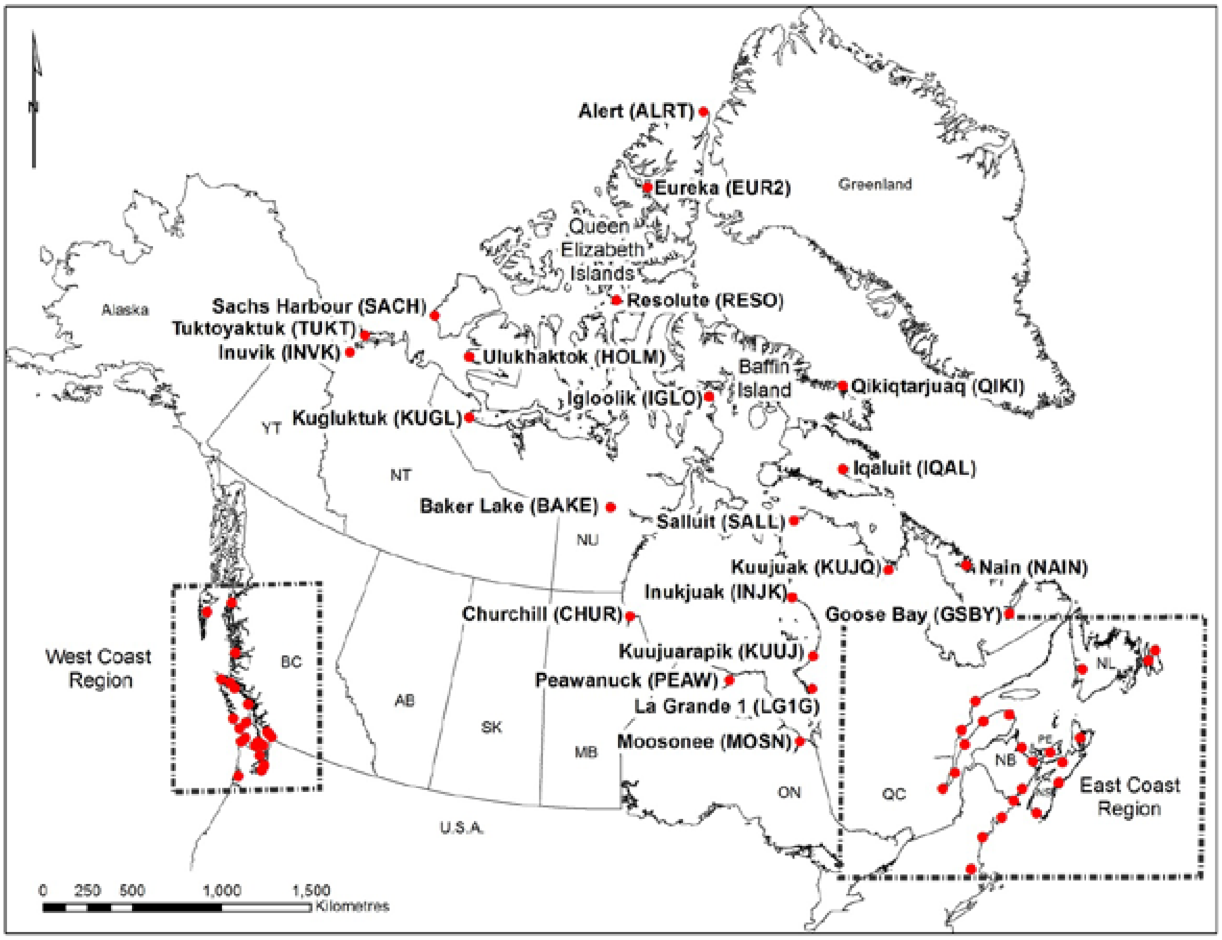

Figure 5. Locations for which sea-level projections were generated (James et al., 2014a). Projections are based on the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5). © Her Majesty the Queen in Right of Canada, as represented by the Minister of Natural Resources Canada, 2014. This is a copy of an official work published by the Government of Canada and it has not been produced in affiliation with, or with the endorsement of, the Government of Canada.

sea-level projections are much smaller and feature both sea-level rise and fall.

A key uncertainty in sea-level projections is the stability of the West Antarctic Ice Sheet. A scenario featuring an additional 65 cm contribution from West Antarctica during this century, added to the median projection of RCP8.5, reduces projected sea-level fall and gives larger amounts of projected sea-level rise.

Vertical Motion

New models of the Innuitian and northern Laurentide Ice Sheet provide improved fits to relative sea-level measurements over the past several thousand years and GPS observations of the rate of present-day crustal uplift. The improved ice-sheet models provide revised estimates of the contribution to global sea-level rise since the Last Glacial Maximum (LGM) (Figure 7). For the Innuitian ice sheet, the new model provides an additional 0.6 m of global sea-level rise (Simon, 2014;

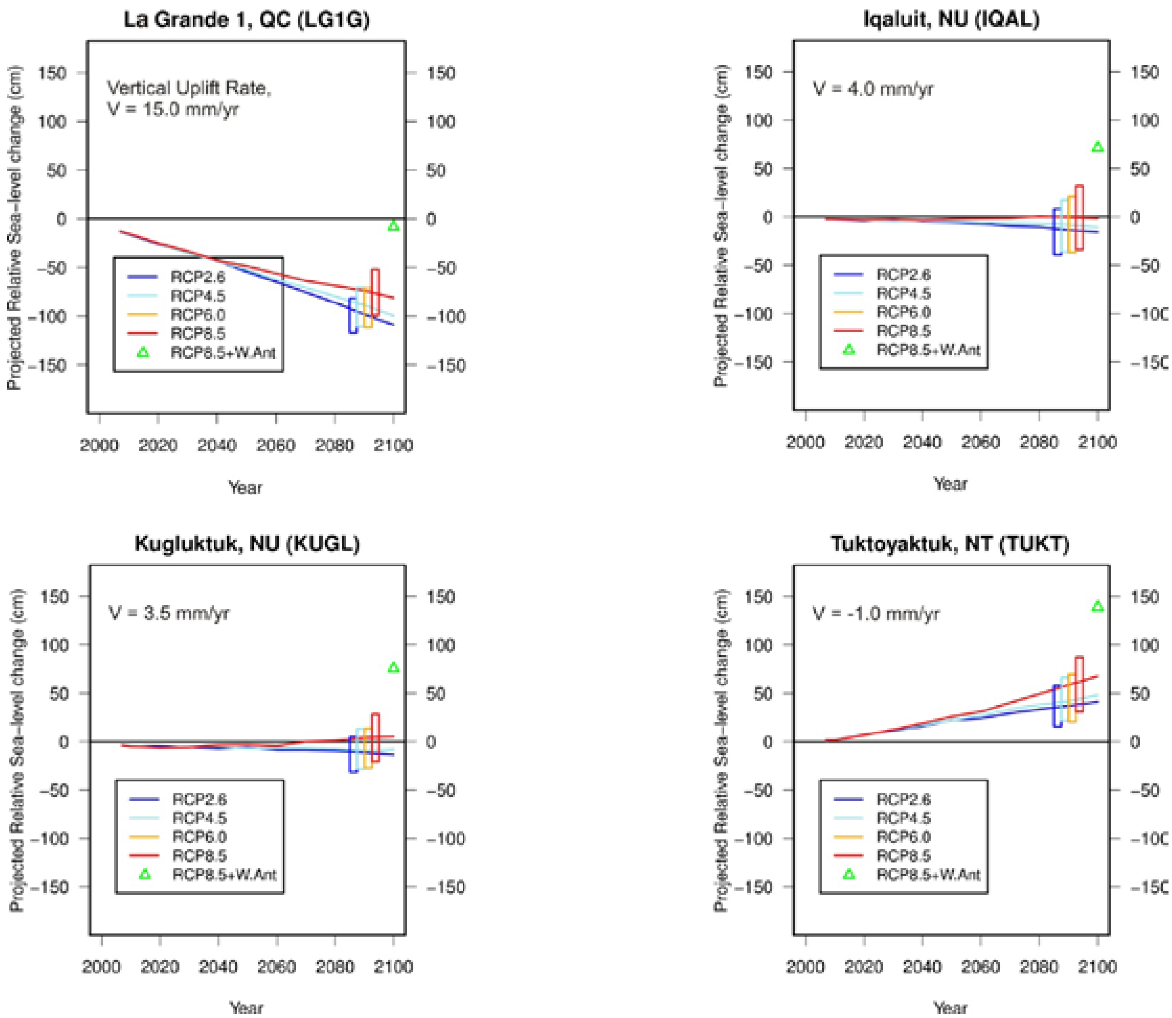

Figure 6. Projected sea-level change through the 21st century at four northern locations, relative to 1995 (adapted from James et al., 2014a). Solid lines show the projected change (median value) through the century for RCP2.6, RCP4.5 and RCP8.5, while rectangles also include RCP6.0 and give the 90% confidence range (5% to 95%) of the average over 2081-2100. The rectangles are distributed over a time range for clarity of presentation, but their mid-point is 2090. Also shown is the projection for a scenario with an additional 65 cm of sea-level rise from West Antarctica, added to the median projection of RCP8.5 (RCP8.5+W.Ant.), is also shown. © Her Majesty the Queen in Right of Canada, as represented by the Minister of Natural Resources Canada, 2014. This is a copy of an official work published by the Government of Canada and it has not been produced in affiliation with, or with the endorsement of, the Government of Canada.

Simon et al., 2015). For the Laurentide ice sheet, the revisions lead to about a reduction of about 8 m in the contribution to global sea-level rise (Simon, 2014; Simon et al., 2014b, 2014c).

Nunatsiavut, Labrador

Fieldwork, which began in the communities of Postville and Hopedale in summer 2013, was conducted in the communities of Nain, Rigolet, and Makkovik in summer 2014. Data were collected for coastal composition and infrastructure, community drainage, and surficial ground

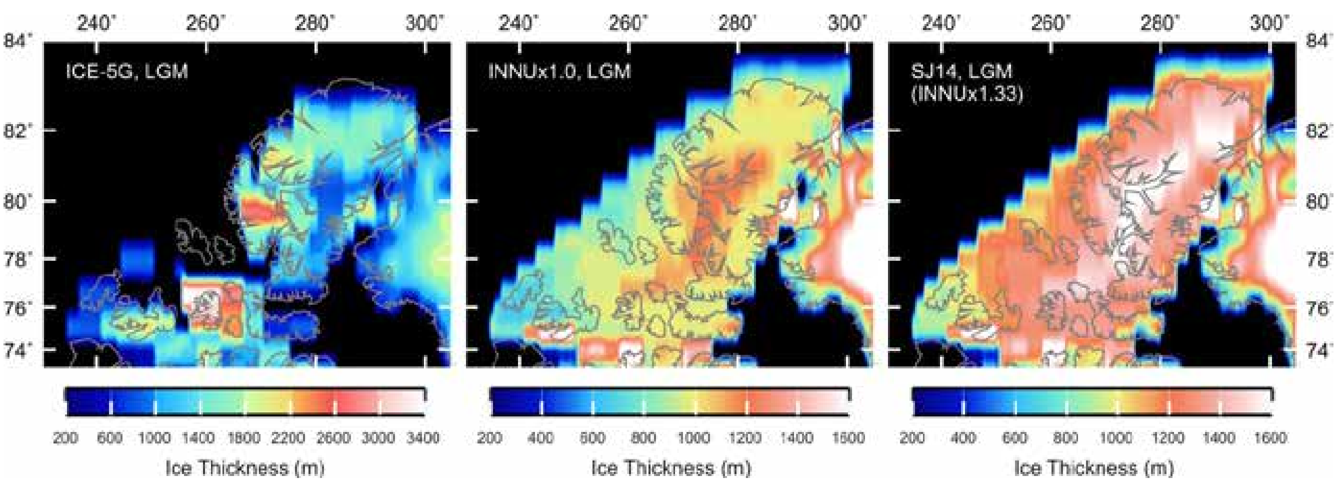

Figure 7. Peak ice thickness at Last Glacial Maximum of the Innuitian Ice Sheet for (left panel) ICE-5G (Peltier, 2004) and the (middle panel) preliminary new model and (right panel) final new model (Simon, 2014; Simon et al., 2015). The initial model developed in this study has peak thicknesses of approximately 1200 m in Eureka and Nansen sounds (middle, INNUx1.0) while the model that best fits the relative sea-level data has peak thicknesses of approximately 1600 m (right, SJ14). SJ14 has ice thickened by a factor of one-third relative to INNUx1.0 and has other local adjustments. From Simon et al. 2015.

cover using a high-precision global positioning system (RTK GPS), soil sampling, and visual observations. Community mapping sessions were also held in Rigolet and Makkovik to determine spaces and places that are valued within the communities (Figure 8). These spaces and places may be valued for a variety of reasons such as cultural heritage, environmental importance, the ability to provide country foods, and transportation. Community participants identified valued areas on maps of their community and described why the areas are important to them and to the community in general. The data for Hopedale, the first community to be completed, have been incorporated into the update of the Hopedale community plan.

Kivalliq, Nunavut

Preliminary landscape hazard mapping for Arviat, based on an initial fast-track assessment in 2009, was published in the past year (Forbes et al., 2014a). The past summer saw the first year of an MSc project on this topic and a large amount of field data was acquired. Initial results suggest that the relatively high temperature of permafrost at this location combined with high residual salinity in the raised marine sediments on which the community is based increase the risk of foundation instability without appropriate adaptation and siting of development. Preliminary analysis of coastal stability issues in this rapidly emerging setting indicates that some parts of the outer coast are undergoing rapid realignment in response to wave action in Hudson Bay and that increasing open water, possibly combined with increased storminess (J.-P. Savard, pers. comm., 2015) may increase the risk of impacts on coastal infrastructure. At the same time, the rapid fall in relative sea level leads to harbour shoaling with potential negative impacts on sealift operations.

Yukon & Northwest Territories

Large volumes of buried ice on Herschel Island and other parts of the southeastern Beaufort Sea coast contribute to rapid rates of shoreline retreat and headwall recession in retrogressive thaw slumps (RTF or retrogressive thaw flow slides) (Lantuit et al., 2012; Forbes et al., 2014b). On-going collaboration between McGill University and the Alfred Wegener Institute

Figure 8. Spaces and places identified as important to the community of Makkovik, Labrador.

(AWI) has enabled the collection of headwall positions of various retrogressive thaw slumps on Herschel Island over a 10 year interval (2004-2014) (Figure 9). Volumetric erosion was highly variable over the study period for 3 RFT systems on the southern shore of the island and retreat rates varied from 5 to 18 m/yr.

Along the 35 km stretch of the Yukon coast between Komakuk Beach and the Canada-USA border, over a 62 year study interval (1951-2013), mean erosion was 1.2 m/yr (250,000 m^3/yr) (Konopczak et al., 2014). Elsewhere along the Yukon coast (Hynes et al., 2014a) and the Mackenzie Delta and Tuktoyaktuk area (Hynes et al., 2104b), locally high erosion rates) have destroyed or threaten archaeological sites, cultural heritage sites (Figure 10), and infrastructure such as the automated weather station on Pelly Island (Forbes et al., 2013). On Richards Island, Pelly Island, and other Pleistocene upland remnant islands north of the Mackenzie Delta, erosion rates (1972-2000) ranged from 0.4 to 1.5 m/yr and locally up to 15 m/yr (Solomon, 2005; Forbes et al., 2014b).

Community Marine Habitat Mapping

Arctic Bay

Completed sediment grain size analyses and ongoing faunal analysis are being used to constrain the multibeam sonar-based benthic substrate and habitat maps for Arctic Bay. While field descriptions of the bottom types ranged from bedrock and boulders to gravelly mud, the sediments collected in the grab samples are dominantly gravel, gravelly sand, or gravelly mud, reflecting the glacial legacy and small catchments of the streams flowing into Arctic Bay, which is overall sediment-starved. The consistent gravel found in all types of sediment leads to a limited range of backscatter values, such that backscatter is much less useful in distinguishing among habitats than in other sub-Arctic and Arctic fjord environments (e.g. Copeland et al., 2012; Carpenter, 2012). Nonetheless, the strongest predictor of acoustic backscatter strength is the proportion of mud (<63 µm). Areas of enhanced sedimentation associated with expanded construction in the Hamlet of Arctic Bay are visible in the multibeam bathymetry and backscatter maps (Figure 11).

From the bottom photographs, stony mud substrates characterize the sediment-starved marine habitats observed within Arctic Bay. Gravel-, cobble- and boulder-sized rock clasts of variable lithologies are recorded commonly in bottom camera images. Most rock clasts are partially covered by crustose calcareous red algae. Brown macroalgae (e.g., *Alaria* sp., *Fucus* sp.) were also observed attached to rock clasts and bedrock outcrops. A thin veneer of fine-grained sediments is observed occasionally on rock surfaces. Dome-shaped *Clathromorphum compactum* and branching *Lithothamnion glaciale* calcareous red algae (often forming rhodoliths) are the most noteworthy of the benthic forms recorded in the bottom photographs. *Clathromorphum* domes are long-lived colonies with century-scale lifespans, whose annual variation in growth

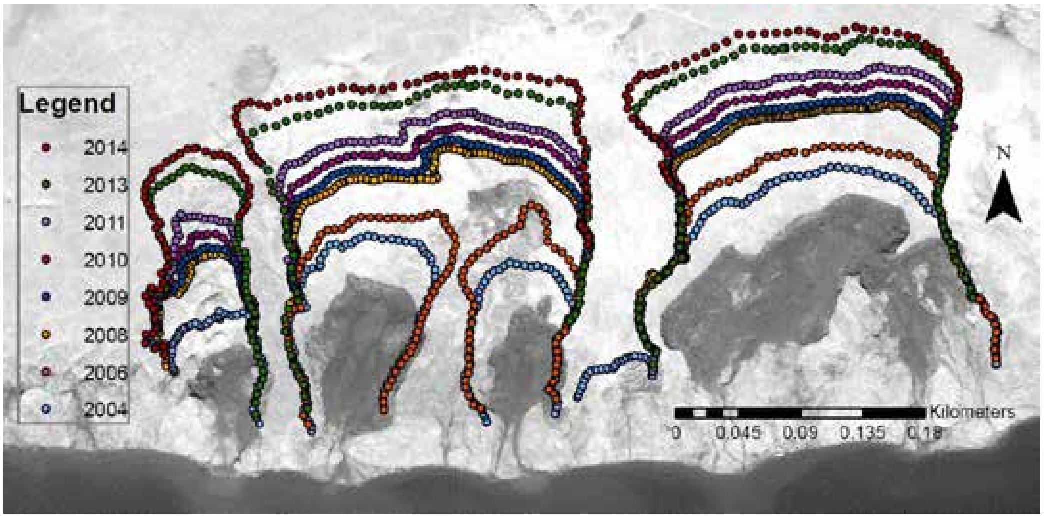

Figure 9. Locations of retrogressive headwalls between 2001 and 2014. Data collected in 2001 from satellite imagery and between 2004 and 2014 using differential GPS.

rates serves as a proxy for sea-ice cover (see Halfar et al. 2013). Sand substrates almost completely covered with filamentous brown macroalgae are also recorded in the bottom photographs. At some stations, particularly those along Adams Sound, and on sandy bottoms near the mouth of the river on the east side of the bay, the canopy of macroalgae obscures the sea bed making observation of the epibenthic organisms challenging. A variety of benthic organisms including molluscs, echinoderms, polychaetous annelids, crustaceans (i.e., sea spiders or pycnogonids, and barnacles), anthozoans, and sponges were recorded in the bottom photographs (Figure 12A-F). The benthic macrofauna observed at Stations 125 and 139 appears particularly rich and includes actinian anemones, brittlestars (ophiuroid echinoderms), sea cucumbers (holothuroid echinoderms), sea lilies (crinoid echinoderms; both *Gorgonocephalus sp*. and *Heliometra sp*.), starfish (asteroid echinoderms), sea urchins (*Strongylocentrotus droebachiensis*) and soft corals.

Figure 10. Erosion threatening historic cabin at Nunaluk Spit, western Yukon coast (photo: D.L. Forbes, GSC, 2012).

Broughton Channel

Preliminary benthic surveys were conducted by Siferd (2005), which provided Mya spp. clam abundance data for Broughton Channel near Qikiqtarjuaq, Baffin Island, Nunavut. Grab samples of seabed substrate and underwater video transects were taken at predetermined locations based on resampling a representative portion of Siferd's (2005) dive sites. Six priority regions were highlighted in and around Broughton Channel (Figure 13), two of which were sampled the previous year (Bell et al., 2013). This year's sampling efforts focused on the completion of four regions, in which 49 video transects, 46 sediment samples, and 74 grab samples were collected. Five prominent seabed types were evident from preliminary analysis of samples. The highest Mya abundance seems to be in sandy sheltered areas (Figure 13 & 14). Mya habitat is therefore likely influenced by both coastal landscape sediments and exposure.

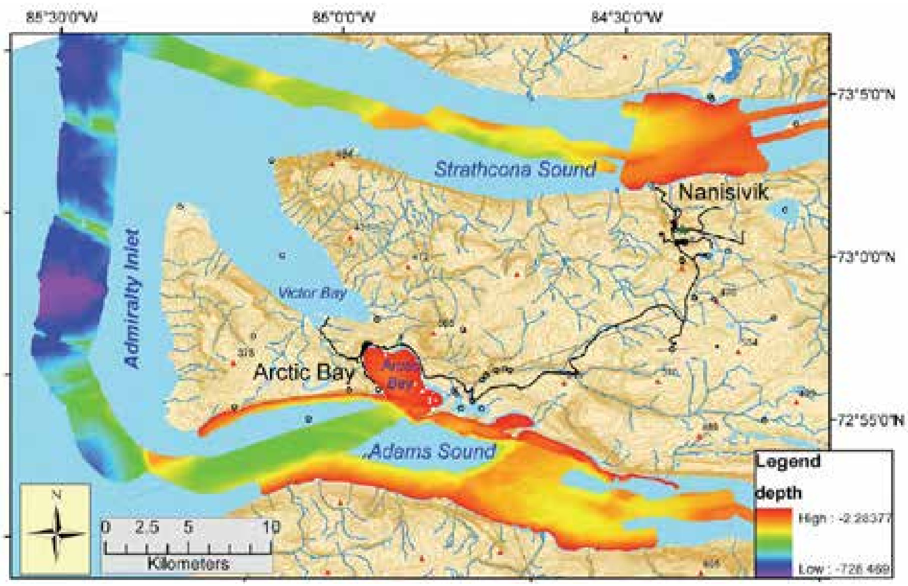

Figure 11. Map showing multibeam bathymetric coverage for Adams Sound, Strathcona Sound, and Arctic Bay. The Arctic Bay habitat mapping project focuses exclusively on Arctic Bay itself and the adjacent shallow waters of Adams Sound. Maximum depths within the bay are 100 m.

Further analysis will be conducted on these data to develop predictive models of clam habitat derived from multibeam echo sounding data.

Community Safe Navigation and Anchorage

Multibeam mapping aboard the GN vessel MV *Nuliajuk* further charted the waters of eastern Baffin Island. This year continued the search for submerged shorelines and lowstand sea-level indicators around Cumberland Peninsula from the past two seasons, and proved successful with the mapping of a submerged delta terrace at -28 m in outer Padle Fiord. Over the course of the multibeam surveys, uncharted corridors and anchorages were mapped in Frobisher Bay, Anderson Channel (Figure 15), and Cumberland Peninsula (Hughes Clarke et al., 2015). In addition to multibeam mapping, equipment was installed on the MV *Nuliajuk* for gravity coring of the seabed. Seven gravity cores were taken within the fjords of Cumberland Peninsula, primarily upon two submerged deltas at -33 m and -37 m in Boas Fiord.

Four piston cores taken around Cumberland Peninsula and Frobisher Bay aboard the CCGS *Amundsen* (2014 Leg 3) add both to the submerged shoreline history and to research that has recently begun on submarine slope instability in Baffin Island fjords. The multibeam bathymetry shows numerous locations of slope failure throughout Frobisher Bay, with scattered examples in other locations such as Mermaid Fiord, suggesting seabed instability and geological hazards in the region (Mate et al., 2015; Hughes Clarke et al., 2015). Cores were taken from prodelta sediments at inner Durban Harbour, within the basin and on the landward side of a fiord-mouth sill platform at -51 m in Akpait Fiord, as well as the site of a submarine mass transport deposit off Hill Island in Frobisher Bay (Figure 16). The delta platform cores were not long enough to penetrate into the deltaic sediments at their respective locations but can be used to determine post transgressive sedimentation rates for a number of fjords. The core proximal to the sill in Akpait fiord has irregular sandy layers, primarily 2.5-5.0 m down-core, indicative of

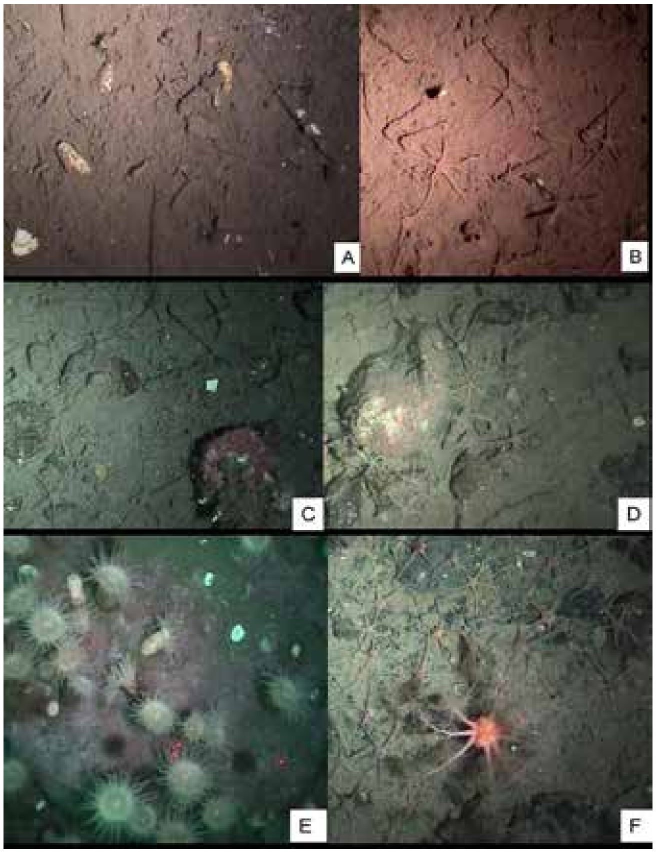

Figure 12. (A) Station 5, Arctic Bay, Nunavut. Water depth is 49 metres. Organisms visible in this image include ophiuroid echinoderms (brittlestars) and onuphid polychaetes. (B) Station 21, Arctic Bay, Nunavut. Water depth is 66 metres. Organisms visible in this image include ophiuroid echinoderms (brittlestars) and onuphid polychaetes. (C) Station 44, Arctic Bay, Nunavut. Water depth is 52 metres. Organisms visible in this image include crustose calcareous red algae encrusting the surface of a cobble, ophiuroid echinoderms (brittlestars) and onuphid polychaetes. (D) Station 50, Arctic Bay, Nunavut. Water depth is 48 metres. Organisms visible in this image include crustose calcareous red algae encrusting the surface of a cobble and ophiuroid echinoderms (brittlestars). (E) Station 125, Arctic Bay, Nunavut. Water depth is 39 metres. Organisms visible in this image include crustose calcareous red algae, actinian anemones, and echinoid echinoderms (sea urchins). (F) Station 165, Arctic Bay, Nunavut. Water depth is 56 metres. Organisms visible in this image include a holothuroid echinoderm (holothurian) and ophiuroid echinoderms (brittlestars).

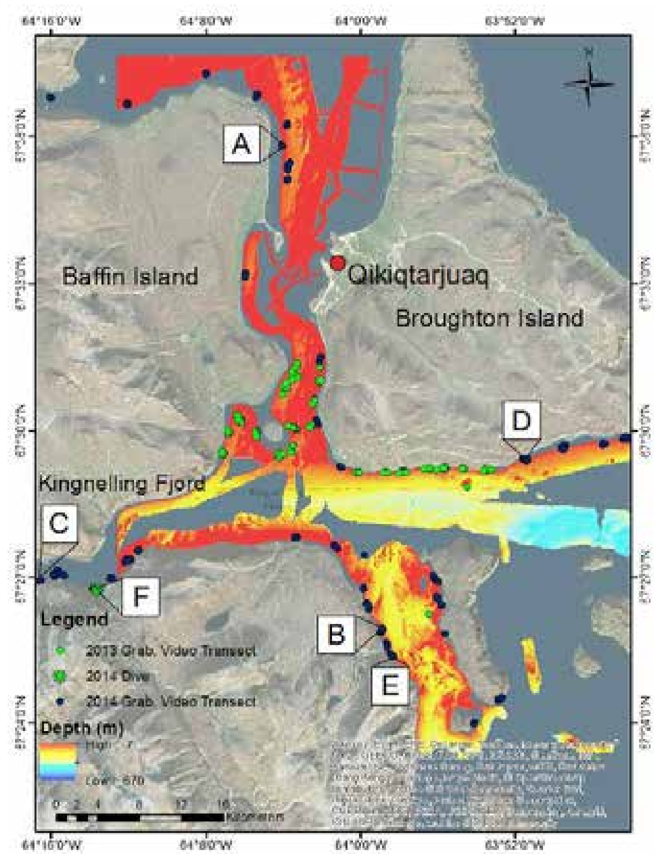

Figure 13. Multibeam bathymetry from MV Nuliajuk of Broughton Channel and surrounding area. Included are locations of video transects and grab samples from 2013 and 2014. (A) Sand/ mud with high occurrence of Mya spp. (B) Cobble/boulder areas included a variety of organisms (e.g. anemones, urchins, crinoids) and scattered clams. (C) Sand/cobble with small patches of clams, although not as densely populated as A. (D) Exposed sand along the southern shore, were devoid of clams. (E) Kelp on boulder or bedrock holdfasts, with some invertebrates e.g. urchins, anemones. (F) The site known to local divers as the best for clam harvesting, which is typically in sand or rocky-sand habitats.

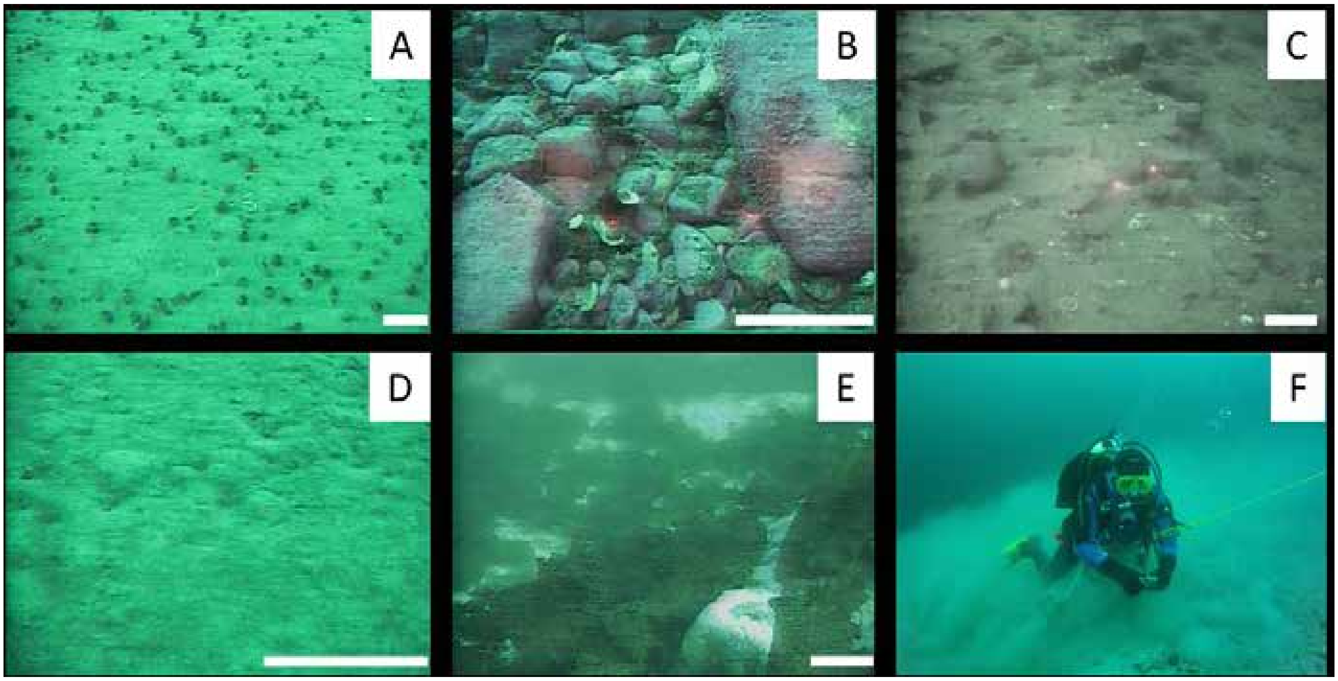

Figure 14. Bottom photographs of the various substrate and benthic habitats within and surrounding Broughton Channel, located in Figure 13. White scale bar represents 10 cm.

overwash events when relative sea level was much lower in the outer Cumberland Peninsula region. The presence of intact shells in the silty sediments surrounding these sandy layers allows for the dating of these events, which will help to constrain the relative sea level history of the region. The core taken off Hill Island in Frobisher Bay shows a clean contact between undisturbed basin sediments and overlying submarine mass movement sediments at 3.1 m down-core, indicative of the slip plane of the original event. Above this point in the core there are a number of coarser grained layers, possibly indicative of subsequent smaller scale events occurring in the footprint of the original mass movement. Again, the presence of shell material allows for the constraining of the date of the original mass movement at this location. Shells have been sampled within the cores to provide age constraints and sedimentation rates from each of the respective core locations.

DISCUSSION

In last year's report, we reviewed the progress of three important milestones: 1) Coastal hazards and change- forcing and response, 2) Landscape and seabed mapping-hazards and change detection, 3) Safe and sustainable communities. This year's activities have been focused on milestone 3) Safe and Sustainable Communities. The work plan for this year was focused on strengthening our community-engaged projects with an expanding international emphasis. In addition, we have used our leadership and knowledge from these projects to further develop and lead a circumpolar observatory network.

Circumpolar Arctic Coastal Communities Observatory Network (CACCON)

This network of interlaced local knowledge hubs was initiated in 2014 with seed funding from IASC as an

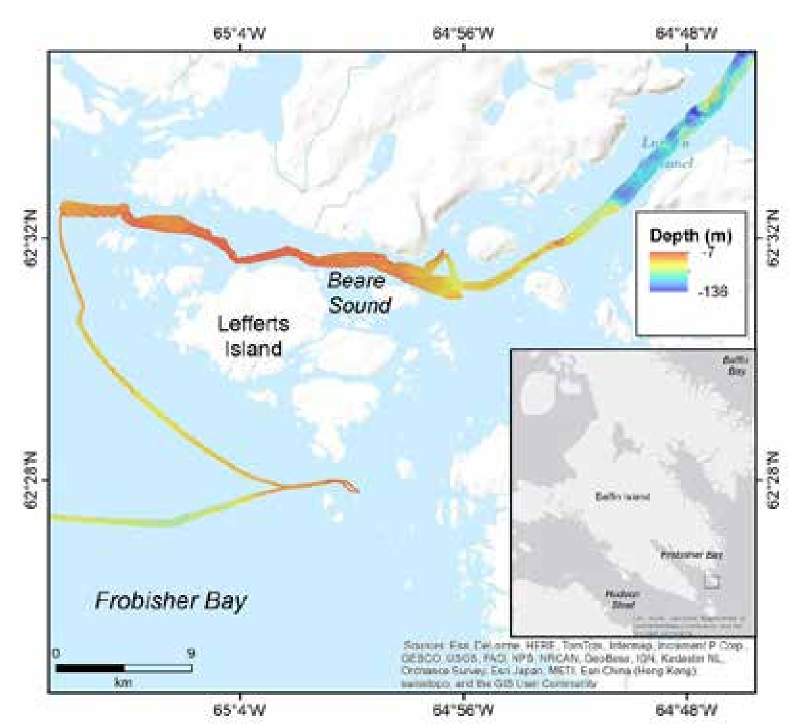

Figure 15. Multibeam coverage of transit corridor and anchorage locations within Beare Sound, through Anderson Channel. Inset is a map of southern Baffin Island, with the location of Anderson Channel outlined at the southeast extent of Frobisher Bay.

ICARP-III project, and from LOICZ (Land-Ocean Interactions in the Coastal Zone, now Future Earth – Coasts) as an emerging northern regional node, together with other LOICZ/FE-C nodes around the world. In the nascent Future Earth – Coasts vision of locally-driven, solutions-oriented, co-designed and co-produced knowledge acquisition and management for sustainable coastal development, CACCON is a perfect fit. It is also consistent with efforts to spread this vision to a wider Arctic community, in the context of ArcticSTAR, a Future Earth –sponsored collaboration between ArcticNet/CACCON, colleagues at the Institute for Advanced Sustainability Studies (IASS) in Potsdam, the Earth Institute and Department of Chemical Engineering at Columbia University in New York, and the Arctic Institute of North America in Calgary.

Coastal Community Climate

Analyses of low-visibility patterns throughout the Arctic are important for three reasons. First, the specifics of timing and reasons for the occurrence of low visibility can directly inform planning. For example, gaining a better idea of when during the day fog/low visibility is likely to occur can aid aircraft scheduling to avoid known foggier periods in the day and so reduce the likelihood of delay. In this case fewer aircraft movement operations could be scheduled for the early afternoon when fog tends to be more common. Information about seasonal and geographic patterns likewise can inform decisions concerning placement of infrastructure. Second, assembling analytical results for these phenomena will feed into numerical weather model verification. Fog and low-visibility are some of the hardest things to get correct for numerical models; this sort of "ground truthing" information is key to their improvement. Third, this information feeds directly into

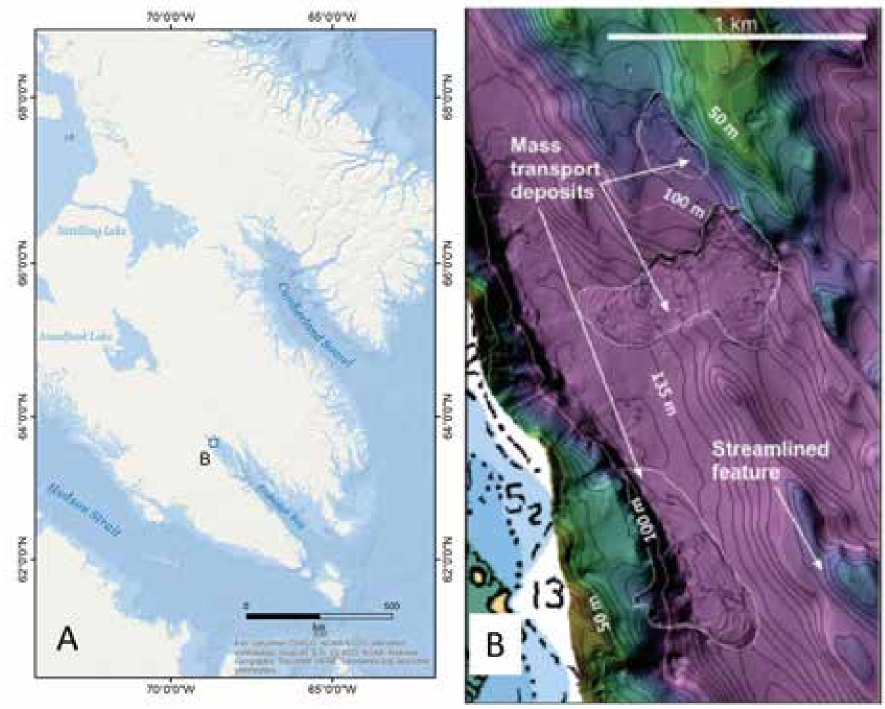

Figure 16. (A) Map of southeastern Baffin Island, with location of Figure 15 B at the head of Frobisher Bay. (B) Multibeam bathymetric image of submarine slope failures in Frobisher Bay, offshore Hill Island. The slope failures clearly stand out from undisturbed seabed that surrounds them. The close proximity of these three features shows the high potential for failures in this environment (from Mate et al., 2015). © 2015 by Canada-Nunavut Geoscience Office. All rights reserved. Electronic edition published 2015. This does not constitute an endorsement by the Canada-Nunavut Geoscience Office.

establishing the linkages between local scale weather response and the large-scale synoptic activity that is driving it. Identification of synoptic (pressure) patterns that drive problematic weather can be used to inform future projections of their increase over time.

Community Hazard Mapping

Projections of sea-level change through the century provide a basis for evaluating flood and inundation risk, in the case of projected sea-level rise. For projected sea-level fall, there are potential risks to navigation (reduced depth-under-keel) and reduced utility of infrastructure built at the water's edge. Both sea-level rise and sea-level fall lead to habitat changes in the coastal zone. The sea-level projections (James et al., 2014a) provide a means to determine the impacts of sea-level change and devise adaptation measures.

For example, for the Northwest Territories, it is anticipated that the sea-level projections will be utilized to update the NWT state of the environment report, to inform the NWT territorial emergency plan, to consider the impacts of sea level rise on the Inuvik to Tuktoyaktuk highway, to plan community development and infrastructure in the four coastal communities, and to consider coastal erosion and habitat loss in the outer Mackenzie Delta. As well, a climate change risk assessment of hazardous waste sites in communities along the Beaufort coast will utilize sea-level projections to help prioritize.

The improved glacial isostatic adjustment model provides revised estimates of the size of the Innuitian and Laurentide Ice Sheets (Simon, 2014). Compared to the starting ICE-5G model, the new models reduce by more than 7 m of equivalent global sea-level the contribution to global sea-level rise. To make up the new shortfall, the southern portions of the Laurentide ice sheet, or the other large ice sheets (Fennoscandian, Antarctica, Greenland) will need to be adjusted and increased in size to make up the shortfall in the global sea-level budget. These adjustments will have implications for sea-level change, vertical crustal motion and the other geophysical effects arising from glacial isostatic adjustment in these regions.

The new models improve the fit to GPS-constrained vertical crustal motion and can be used to predict vertical crustal motion at locations where there are no observations. Among other things, they could provide an improved estimate of the gravitational signal arising from glacial isostatic adjustment to correct satellite gravity observations (e.g., Gravity Recovery and Climate Experiment, GRACE) for GIA in order to isolate the hydrological effects.

A comparison of our results of erosion rates of the 35 km stretch of the Yukon coast between Komakuk Beach and the Canada-USA border with studies carried out in Alaska (Ping et al., 2011; Brown et al., 2003; Jones et al., 2009) suggests an overall spatial pattern of decreasing erosion rates from west to east despite similar exposure to the direction of major storm events and comparable geology. With increasing open water in this part of the Beaufort Sea, there is a potential for accelerated coastal erosion in the future. Farther east in the Canadian Beaufort, rapid rates of delta-front loss in the Mackenzie Delta (Hynes et al., 2014b) and rapid erosion on islands north of the delta and eastward along the Tuktoyaktuk Peninsula are already threatening cultural resources, critical infrastructure (e.g. weather station on Pelly Island), and coastal habitat integrity. Coastal retreat at the Pelly Island weather station has amounted to 1200 m since 1950 (D. Whalen, pers. comm., 2015), an average of >18 m/yr over 64 years.

Community hazard mapping in Arviat is providing ground-truth for GN-sponsored mapping of surface seasonal disturbance and inference of near-surface ice content. In this way it contributes to the planning process. With installation of the ADAPT permafrost monitoring station in this relatively low-latitude site with warm, saline permafrost, it provides a basis for understanding the sensitivity of permafrost and ground ice in both the local community and the broader region. As in Nunatsiavut, knowledge gained from the landscape hazard mapping can support a diversity of issues and decision-making, including social issues such as food security, health and well-being, safety and security and valued places.

Over 75% of surface salt accumulations (like those found on Axel Heiberg Island) correlate with local geomorphic disturbances such as gullying, active layer detachments and retrogressive thaw slumping (Kokelj and Lewkowicz, 1999). Salt has a depressed freezing temperature when compared to water so an increased salt content within the environment (i.e. from runoff from salt deposits or from thawing saline permafrost, as found on Herschel Island) can further thaw permafrost driving geomorphic change and can negatively affect plant communities (Kokelj et al., 2002).

Community Marine Habitat Mapping

Arctic Bay

A recent pan-Arctic inventory of the species diversity of the macrofauna and megafauna inhabiting Arctic shelf seas identified the waters bordering the Canadian Arctic Archipelago as some of the most poorly explored marine habitats in the circumpolar North (Archambault et al., 2010; Piepenberg et al., 2011). The study of the marine benthos inhabiting Arctic Bay, Nunavut, represents our effort to address this paucity of data related to benthic community structure and species diversity. We are combining our shallow water Arctic biodiversity data from these high Arctic locations and Labrador fjords (Brown et al. 2012) to examine biogeographic patterns, which can be compared with those described from deep waters of the Canadian Arctic (Roy et al, 2014). The soft-bottom benthic fauna recorded from Arctic Bay consist of a variety of organisms that occur commonly and often abundantly in the shallow marine benthos inhabiting the CAA (Ellis, 1960; Thomson et al., 1986; Aitken et al., 1988; Dale et al., 1989; Aitken and Gilbert, 1996; Conlan and Kvitek, 2005; Dale and Leontowich, 2007; Brown et al., 2011; Piepenburg et al., 2011; Roy et al., 2014). These organisms include the bivalves *Astarte borealis*, *Astarte montagui, Ennucula tenuis, Hiatella arctica, Macoma calcarea*, and *Nuculana pernula*, the limpet *Lepeta caeca*, the brittlestars, *Ophiocten sericeum* and *Ophiura robusta*, and the sea urchin, *Strongylocentrotus droebachiensis*.

The most common organisms recorded in the bottom photographs from Arctic Bay are onuphid polychaetes (i.e., recorded as characteristic tubes encrusted with coarse sand grains) and brittlestars. Onuphid polychaetes have been identified as indicator species for benthic habitats characterized by low sedimentation rates and consolidated substrates within Baffin Island fjords (Dale et al., 1989; Syvitksi et al., 1989; Aitken & Fournier, 1993). A variety of ophiuroid echinoderm taxa are recorded as dominant taxa in both soft-bottom and hard-bottom macro- and megabenthic communities inhabiting shelf seas along the Arctic coastline of Canada (Stewart et al., 1986; Dale et al., 1989; Roy et al., 2014).

The stony mud substrates observed in Arctic Bay are characterized by coralline algae-encrusted cobbles. The coralline algae are observed as thin crusts or 3-dimensional forms exhibiting dome-shaped or branching morphologies (rhodoliths) on cobble surfaces. We have also observed crustose coralline algae on cobble surfaces sampled from Broughton Harbour in the vicinity of the community of Qikiqtarjuaq, Nunavut. Coralline algae in the Canadian Arctic Archipelago are under-reported. Crustose coralline algae (e.g., *Clathomorphum circumscriptum*) have been observed on the surfaces of boulders and steeply sloping rock surfaces on the sidewalls of several Baffin Island fjords (Kent, 1972; Dale et al., 1989; Aitken, unpublished). Substrates consisting of large proportions of gravel, cobbles and boulders support epifaunal communities consisting of sponges, basketstars (*Gorgonocephalus* sp.), crinoids (*Heliometra* sp.), sea urchins (*Strongylocentrotus* sp.), brittlestars (e.g., *Ophiocantha* sp., *Ophiopus* sp.), sea anemones and soft corals (Dale et al., 1989; Roy et al., 2014). This full suite of organisms has been observed in association with rhodoliths at many stations in Arctic Bay.

Because coralline-algal habitats support high biodiversity and are dependent on light and exposed hard substrates, they are sensitive to sedimentation. In Arctic Bay, we observed *Lithothamnion* rhodoliths covered in muddy sand near stream mouths, and near the community. The increased sediment load appears to come from several sources. First, climate change is bringing more rain, and in particular, more intense rain events to the High Arctic. We observed a torrential thundershower in Arctic Bay, followed immediately by extreme overland flow and stream discharge, which brought a high sediment load to the nearshore areas of the bay close to the community, and close to river mouths. Expansion of the community also exposes more soil, increasing the sediment load in overland flow. Finally, climate change increases rates of permafrost degradation and gelifluction, with the displaced soil and sediments then eroded at the shoreline and transported into the bay. Although we documented dramatic permafrost degradation in certain locations of Arctic Bay, we were not able to quantify rates of gelifluction-related coastal erosion.

Broughton Channel

The benthic survey of Broughton Channel, near the Hamlet of Qikiqtarjuaq, represents a co-production of knowledge between the Memorial University Marine Habitat Mapping Group (MhMg), Government of Nunavut (GN), and community of Qikiqtarjuaq. This project has established baseline data in order to assess the potential for a commercial, community-based fishery in Qikiqtarjuaq. Inuit divers from the community have harvested clams locally for the past decade; in order to continue developing this resource, scientific and community objectives regarding the harvesting of clams must be addressed. Scientific objectives include identifying substrate, depth, and coastal geomorphological features that are conducive to *Mya* clam presence. Also of interest is the transferability of clam habitat prediction tools to other areas in the Arctic, and eastern Canada, to assess the potential for developing clam resources elsewhere. Community objectives include developing local clam resources for economic support and for food security, while being mindful to not deplete this resource.

In addition to samples that were collected over the past two field seasons, further work is planned for local divers to sample clams for density and growth research. This benthic survey is the first part of a four year commercial harvesting plan co-designed by the MhMg and GN for the assessment of a small-scale commercial clam fishery in Qikiqtarjuaq, NU.

Community Safe Navigation and Anchorage

The primary objective of the MV *Nuliajuk* multibeam surveys was to map the uncharted waters of eastern Baffin Island, in particular transit corridors and anchorages. The data acquired contribute to the knowledge and maps of Canadian landmass and coastal waters, and provide further constraints on the submerged sea-level history of Cumberland Peninsula. The addition of another submerged delta terrace site to the other nine submerged shorelines from the previous reports, has confirmed the eastward tilt of the Holocene lowstand across the northern peninsula. This dataset contributes to the understanding of vertical motion and sea-level change to improve our understanding and projections for future change in nearby communities.

The multibeam surveys also contributed bathymetric datasets for the benthic habitat mapping project near Qikiqtarjuaq, which is of interest to GN for its potential as a commercial clam fishery. Finally, it is from the multibeam mapping that submarine slope failures have been identified for both geomorphic analysis and marine sediment core analysis. The sedimentary sequences in mass transport deposits provide an important archive of past earthquakes, and can be extended to other mapped fjords and inlets. This research will address issues of slope stability and geological hazards by mapping their distribution and adding to the knowledge of recurrent hazard events. Further research will improve our understanding of tsunami risks to coastal and seabed infrastructure (Mate et al., 2015).

CONCLUSION

The diverse suite of 2014 project activities documented above were all ultimately directed to improved knowledge of environmental hazards, resources, and change confronting coastal communities in the Canadian Arctic. Also many of the activities described here were conducted in close collaboration with northern partners, the development of the Circumpolar Arctic Coastal Communities Observatory Network (CACCON) represents a step-change in our commitment to co-design and co-production of situational (environmental and social) knowledge for future sustainability. Arctic communities face an array of social, economic, environmental, and technological change that place severe strains on adaptive capacity and resilience. The work undertaken in this project has contributed in some measure to alleviating some of these strains and is helping to build local environmental knowledge and capacity in partner communities.

ACKNOWLEDGEMENTS

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UNDERSTANDING AND RESPONDING TO THE EFFECTS OF CLIMATE CHANGE AND MODERNIZATION IN NUNATSIAVUT

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ABSTRACT

Nunatsiavut Nuluak is addressing Inuit concerns about the impacts of climate change and modernization on the health of coastal ecosystems and communities of northern Labrador. The overarching goal is to provide meaningful and timely research on regionally identified priorities while involving Inuit and Inuit Knowledge in all aspects of the project. The first cycle of research activity focused on data collection throughout northern Labrador, with an emphasis on fjord ecology and marine systems along the north coast. In ArcticNet's second cycle the project is concentrated on coastal regions that are, or in the future may be, subject to the dual stressors of climate change and industrial activities. Specifically, Phase III field activities focus on Lake Melville, an estuary downstream from a sanctioned hydroelectric development. The research program, officially called 'Lake Melville: Avativut, Kanuittailinnivut' (Our Environment, Our Health), is establishing baseline conditions for Inuit health, community wellbeing and ecosystem integrity prior to industrial hydroelectric development upstream of Inuit territory. It is also developing the science for monitoring the effects of industrial activity on subarctic estuaries and coastal Inuit communities in the context of ongoing climate change impacts.

KEY MESSAGES

ArcticNet's Nunatsiavut Nuluak research program studies the impacts of climate change, modernization and contaminants on the health of ecosystems and communities in and adjacent to Nunatsiavut, the Labrador Inuit Land Claims region. In Phase 3 of ArcticNet, our program focused on Lake Melville: Avativut, Kanuittailinnivut, a Nunatsiavut Government-led research and monitoring program to study the downstream effects of the proposed Lower Churchill project on Inuit community health and well-being in the Lake Melville region.

- Observations and model simulations show that the dominant component of the currents in Lake Melville is driven by diurnal and semi-diurnal tides, which strongly influence at least two elements of the regional oceanographic dynamics: circulation and vertical mixing.
- Understanding the impact of tidal dynamics on the physics of Lake Melville is essential for interpreting the response of the Lake Melville to natural and anthropogenic factors.
- Radiochemical and geochemical data for seabed sediment samples in Lake Melville, together with detailed bathymetric and backscatter maps and sub-bottom acoustic profiles of selected areas, provide a means of identifying locations of net deposition and erosion, which supports interpretation of benthic habitat data and also provides a means of estimating the capacity of sediments to capture and bury total and methylmercury (MeHg) inputs to the system.
- Although sedimentation and biomixing (bioturbation) rates appear to be controlled in part by local or regional sediment supply (e.g., proximity to major rivers, Goose, Northwest, and Churchill), a larger-scale depth-dependence of these rates provides a means of estimating the total sedimentary sink in the system and thus constructing a budget in which this key component is robust.
- Salinity and water column stratification exert a major influence on MeHg production and bioaccumulation in Lake Melville.
- Mass budget calculations reveal water column methylation is the largest annual MeHg source to seawater, followed by external inputs from rivers, and benthic sediment is a net sink.
- Bioaccumulation factors increase sharply in the smallest size fraction of zooplankton and are higher than in mid-latitude marine systems,indicating enhanced biological uptake of available MeHg.
- From the 1970s through the late 1990s, the impacts of anthropogenic climate change were largely obscured by slow-varying (low frequency) variability in Labrador; in recent years, this same variability has enhanced regional warming.
- Climate change in Labrador is most apparent in winter. In some years, this winter warming has included prolonged thaw events.
- Extreme warm winters and winter thaw events are driven by variations in local atmospheric circulation; the negative phase of the North Atlantic Oscillation (NAO) captures some of this variability, but remains an imperfect predictor of Labrador winter temperatures.
- During negative NAO events, the number days with extratropical cyclones approaching Labrador from the cold Canadian interior decreases; warm winters then result from a decrease in associated cold air outbreaks, rather than an increase in the number of warm systems.
- A benthic biotic and abiotic monitoring program was established for the Lake Melville basin.
- A sea-ice monitoring program was launched in Upper Lake Melville.

OBJECTIVES

The primary goals of Lake Melville: Avativut, Kanuittailinnivut are to establish baseline lake conditions and develop the science for monitoring the downstream effects of hydroelectric development prior to any Lower Churchill development in the context of Inuit health, community wellbeing and ecosystem function/integrity and against a background of ongoing climate change impacts. Specifically, our objectives are:

- To conduct high resolution marine geophysical surveys in Lake Melville in support of seabed mapping and sampling, substrate characterization and sampling, benthic habitat classification and sampling, and oceanographic monitoring and modeling;
- To determine the factors that regulate the physical oceanography of Lake Melville, with special emphasis on the sill, which plays a primary role in determining the mixing that influences the water properties of the Lake and the transport of freshwater and contaminants to coastal Labrador;
- To understand how changes in freshwater runoff have influenced the oceanography of Lake Melville; in particular, how the changes in freshwater runoff, both in degree and timing, have influenced the exchange characteristics and heavy metal retention in the lake;
- To understand how climate change has influenced the oceanography of Lake Melville and the exchange dynamics, with a particular focus on the changes in coastal oceanographic conditions and atmospheric forcing;
- To quantify the relative contributions of anthropogenic activity and natural climate drivers on central Labrador climate and to investigate the physical processes underlying Labrador climate variability;
- To establish a sea ice climatology and history for Lake Melville, identify trends/variability in timing of freeze-up and thaw, and establish a sea ice monitoring program;
- To understand how sea-ice dynamics in Lake Melville are tied to the freshwater cycle and the mixing dynamics at the sill and how the formation and breakup of sea-ice is related to freshwater runoff and exchange control at the sill;
- To develop sediment and organic carbon budgets of Lake Melville to identify the major processes responsible for the overall functioning of the system and to characterize the components within the system that may be sensitive to hydrological or climatic changes;
- To determine current and recent (100 years) rates of sedimentation and organic carbon and nitrogen burial within Lake Melville to assess any past or future changes to the estuary as a result of climate change and/or industrial activity upstream;
- To quantify the major sources of methylmercury to biota in Lake Melville, characterize the influence of climate-driven physical and chemical variability in the ecosystem on methylmercury dynamics, and quantify the potential impacts of hydroelectric development on the lower Churchill river on fish and seal methylmercury levels;
- To identify and understand baseline environmental health status in Lake Melville communities;
- To identify / generate key indicators of community and environmental health to monitor over time before, during and after hydroelectric development.

INTRODUCTION

ArcticNet's Nunatsiavut Nuluak is a research program that studies the impacts of climate change and modernization on the health of ecosystems and communities in and adjacent to Nunatsiavut, the Inuit Land Claims region of northern Labrador. The current project emphasis is concerned with coastal regions that are, or in the future may be, subject to the dual stressors of climate change and industry-related activities. Lake Melville, the current focus of research activities, is an estuary downstream from established and proposed hydroelectric development (Figure 1).

Since 1970, the Churchill River in central Labrador has been diverted from its natural channel through a hydroelectric power generating station at Churchill Falls and the headwaters have been controlled through the creation of the Smallwood Reservoir. The downstream effects of this Upper Churchill project on Lake Melville, the large saltwater estuary that drains the Churchill River into the Labrador Sea, are largely unknown, although recent fish studies have documented elevated mercury levels and local residents have observed changes in wildlife, sea ice, water quality, and climate, among others, since the 1970s. A second hydroelectric scheme, the Lower Churchill project, is now proposed for the Churchill River at Muskrat Falls, about 25 km upstream of Lake Melville. Flooding of its associated 59-km-long reservoir is scheduled to begin in 2015.

Lake Melville: Avativut, Kanuittailinnivut is a Nunatsiavut Government-led research and monitoring program to study the downstream effects of the proposed Lower Churchill project on Inuit community health and well-being in the Lake Melville region. The Labrador Inuit Settlement Area includes the eastern two-thirds of Lake Melville. Rigolet, the southernmost Nunatsiavut community, is located at the Narrows, where Lake Melville is connected to the Labrador Sea. Significant numbers of Labrador Inuit and land claim beneficiaries live in the two main communities of Upper Lake Melville (ULM); Happy Valley-Goose Bay and North West River. Harvesting of country foods is a central component of traditional Inuit lifestyles in the region and an important cultural activity in the mixed economy of ULM. Winter sea ice travel connects communities at either end of Lake Melville and provides access to country foods.

Two main goals of Lake Melville: Avativut, Kanuittailinnivut are: 1) to establish baseline conditions for Inuit health, community well-being and ecosystem function/integrity in Lake Melville prior to any Lower Churchill development, and 2) to develop the science for monitoring the downstream

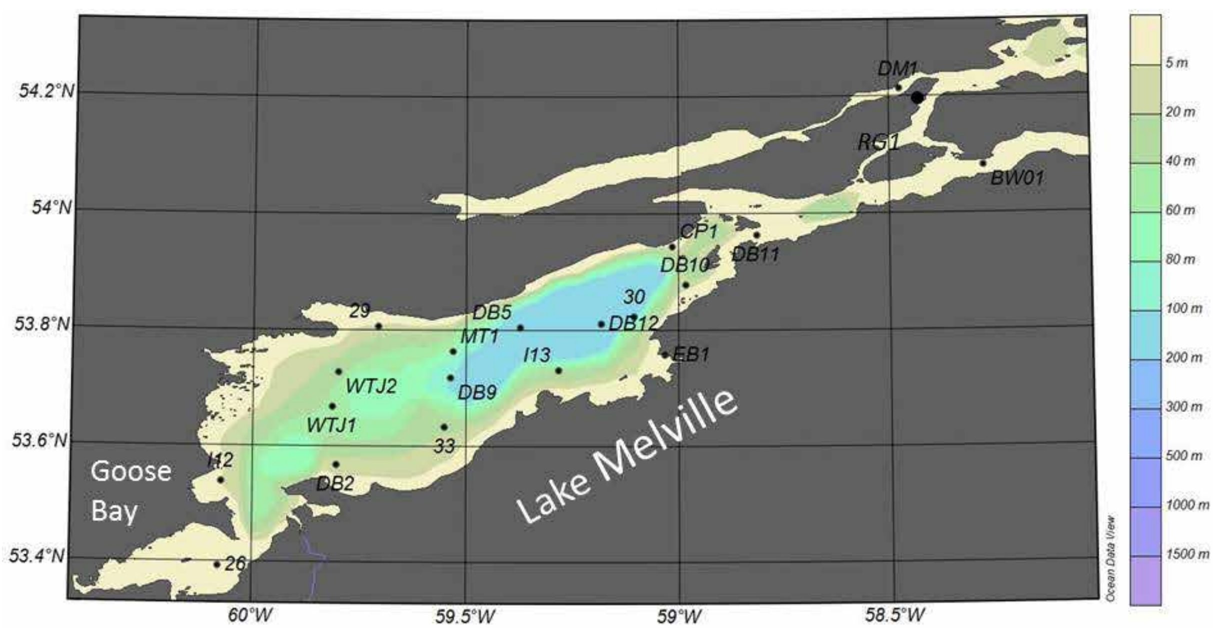

Figure 1. Map showing locations where sediment cores were collected in 2014.

effects of hydroelectric development on a subarctic estuary and coastal Inuit communities in the context of ongoing climate change impacts. Specifically, the project focuses on three interconnected components that directly impact Inuit health: Methylmercury; Ecosystem Integrity, and Community Well-being.

ACTIVITIES

Our research activities and results are prioritized and structured around four key actions in each of the project components: Measuring, Modelling, Monitoring, and Messaging.

Measuring

- Moorings and recording instruments were recovered after 10 months of temperature, salinity and currents measurements in the Lake Melville. These provide the crucial measurements to define the basic description of the seasonal cyclic characteristics of Lake Melville (NIs E. Demirov & B. de Young).
- Completion of a sediment coring program in Lake Melville, designed to provide the basis for constructing a sediment budget and supporting the development of a mercury budget (NI Z. Kuzyk).
- Benthic sediment and biotic samples were collected at sentinel sites in Lake Melville (NI Bell with Carpenter, Laing and Angnatok).
- A dietary survey (including both country and store-bought foods) of Inuit from the Lake Melville region was completed to characterize interseasonal as well as interindividual variability in diet. For each food, survey respondents were asked to quantify their intake over three time periods (the past 24 hours, the past month and the past three months).
- The dietary survey was combined with the optional collection of a hair sample to evaluate the robustness of a baseline exposure model and the robustness of data returned on questionnaires. Mercury analyses are ongoing.

Modelling

- Bathymetric and topographic data were integrated to form a 3-Dimensional dataset for the Lake region, an important input for model simulations (NIs B. de Young & T. Bell).
- Circulation and transport dynamics were simulated through temperature, salinity, and circulation measurements from the past two years, which addressed questions about the paths and age of the freshwater mass inside Lake Melville (NIs E. Demirov & B. de Young).
- The response of Lake Melville and its environment under different climate scenarios was modeled from various long term regional atmospheric characteristics as a function of river discharge to understand the response on temperature, salinity, currents and sea-ice to extreme cold and warm surface water conditions (NIs E. Demirov & B. de Young).
- Development of a preliminary sediment budget for Lake Melville, with emphasis on the supply, distribution and fate of sediment delivered by the Churchill River, provide information on the capacity of sediments to capture and bury total and methylmercury inputs to the system (NI Z. Kuzyk).
- Exploring relationships between regional cyclone activity (storm tracks) and winter warming (NI J. Finnis).
- Statistical modeling of Labrador thaw events as a point process (Coles, 2001) (NI J. Finnis).
- Analysis of trends in Lake Melville sea ice cover; quantifying spatial variability in Melville ice cover, and exploring relationships between

climate variability/change and trends in the length of the ice season (NIs J. Finnis & T. Bell with M. Smith).

- We are developing a preliminary mercury mass budget for the Lake Melville system and using this information to parameterize a dynamic mercury cycling model to investigate the impacts of ecosystem changes.
- We are also developing a mechanistic model for mercury cycling in Lake Melville that relates changes in inputs from atmospheric deposition and riverine inflows to concentrations in fish and seal.
- We are also developing a probabilistic human exposure model based on dietary survey data and anticipated changes in MeHg levels of country foods to estimate future changes in MeHg exposures and health risks for Inuit corresponding to climate variability and flooding of the Lower Churchill River.

Monitoring

- Completion of a final year of measuring and monitoring water column chemistry/ biogeochemistry in Lake Melville (salinity, dissolved nutrients, dissolved organic carbon) (NI Z. Kuzyk).
- Characterization of sediment substrate properties (particle size distribution, organic carbon content, stable carbon isotope composition), using samples collected in 2013 and 2014 in Lake Melville, with the goal of supporting long-term monitoring efforts and differentiating natural and anthropogenic disturbance signals (NI Z. Kuzyk).
- Faunal assemblages of 2013 samples from sentinel monitoring stations were characterized (NI T. Bell with B. Misiuk).
- A sea ice monitoring program was established in Upper Lake Melville (NI T. Bell and R. Briggs).
- We have established a community-based monitoring program to assess seasonal and interannual variability in Hg and MeHg concentrations in freshwater tributaries flowing into Lake Melville as well as mercury concentrations in marine subsistence foods (NI Sheldon with Laing).

Messaging

- Public meetings regarding dietary surveys and hair sampling were held in Rigolet, Happy Valley - Goose Bay and North West River.
- A Facebook page was established to provide information regarding the implementation of the dietary survey and hair sampling. Posts associated with this page have reached up to 4,920 people.
- In September, APTN completed a feature on the dietary survey and hair sampling program with Inuit and research assistants from the Lake Melville region.

RESULTS

Measuring

Vertical profiles of the radionuclides ^{210}Pb, ^{226}Ra, and ^{137}Cs were measured in 11 cores collected throughout Lake Melville in June 2013 and are currently being measured in cores collected in October 2014 (Figure 1). ^{210}Pb derived sedimentation rates (SR) and mass accumulation rates (MAR) (validated with ^{137}Cs) exhibit about four-fold variability throughout Lake Melville (0.08-0.26 cm y^{-1} and 0.06-0.27 g cm^{-2} y^{-1}, respectively; Figure 2). SRs are highest in deep water (161 m) in the west end of the Lake and in shallower water (47 m) off the mouth of the Kenamu River, whereas they are lowest off the mouth of Sabaskatchu River (50 m water depth) and in Grand Trough (213 m water depth). Thus, water depth does not appear to

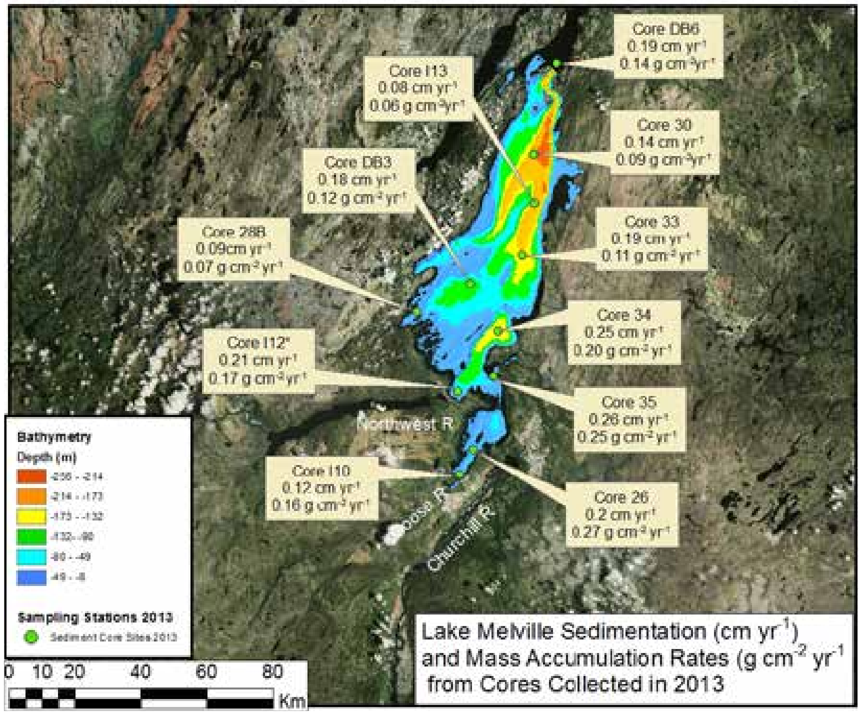

Figure 2. Map showing ^{210}Pb estimated sedimentation (cm yr^{-1}) and mass accumulation rates (g cm^{-2} yr^{-2}) calculated from cores collected in June 2013.

be a straightforward control on SR. In contrast, MARs are linearly related to water depth (R^2=0.65). An even stronger relationship exists between MARs and surface water salinity at the time of sampling (R^2=0.74). MARs are estimated from SARs using sediment porosity, thus the clearer spatial trends in MARs may reflect, in part, the spatial and water depth-related trends in particle size. Organic carbon concentration (OC) in surface sediments increased along a west to east transect from Goose Bay (0.4-1.1%) to the easternmost portion of Lake Melville (1.7%). Outside the Narrows, in Groswater Bay, OC decreased slightly to 1.4%.

Observations of water properties such as salinity and nutrient concentrations were obtained in Lake Melville from the spring/early summer period (June), which is approximately the period of peak river discharge. At that time of year, Lake Melville was stratified with warm (1-10°C), low salinity (3-20) water occupying the top ~20 m and cold (<1°C), high salinity (>25) water below a depth of 50 m. In addition to freshwater, the Goose, Churchill and Northwest rivers were supplying nutrients, especially nitrate, to the Lake Melville system (average concentrations of 4.3 uM, 1.9 uM, and 2.2 uM, respectively). The rivers were acting as much weaker sources of phosphate (concentrations ≤0.1 uM) and silicic acid (0-4.7 uM). The marine waters flowing into Lake Melville from Groswater Bay contained similar or slightly higher concentrations of nutrients compared to the river water (~4 uM, 0.3 uM, and 12 uM for nitrate, phosphate and silicic acid, respectively). The highest nutrient concentrations in the system were found in the deep waters of Lake Melville (~7.5 uM, 0.7 uM, and 17 uM for nitrate, phosphate and silicic acid, respectively; Figure 3).

Despite June being typically a productive season in northern coastal areas, nutrients in surface waters in Lake Melville were not completely depleted at any site sampled in June 2013. Secchi disc measurements

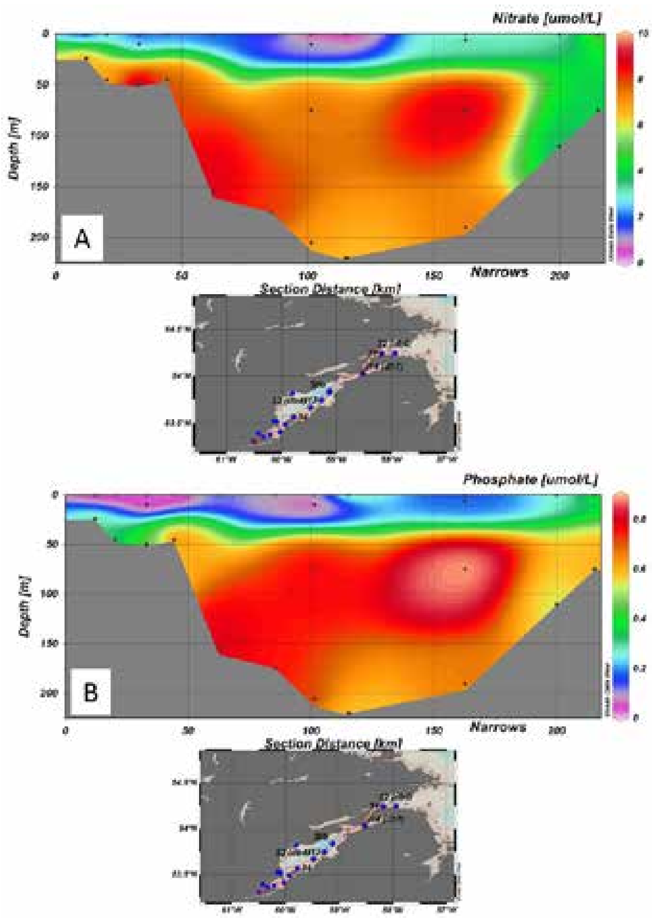

Figure 3. Ocean Data View (ODV) images showing nitrate (A) and phosphate (B) distribution in Lake Melville in June 2013.

indicated a very shallow (<2 m) depth of light penetration into the water column throughout the Lake. Immediately outside (east of) the Narrows, the clarity of the surface waters was vastly improved (secchi disc measurements of 4.5-5 m). Phytoplankton biomass (measured as chlorophyll a) was higher in Groswater Bay than at any Lake Melville sites. Additional water quality samples collected in Lake Melville in October 2014, which are in the process of being analyzed, will provide a seasonal comparison of properties, and, in particular, insight into the effects of fall waves and storms on surface temperature, salinity and nutrient concentrations.

The hydrographic data for the Lake confirm that it is an estuary with typically warm fresh surface water overlaying colder more saline water. The surface water varied in thickness along the axis of the Lake but was typically 20m thick. The surface salinity varied from 12 psu at the surface to 22 psu at 20 m depth. Of course water outside the sill is more saline, typically 30 just below the sill outside the Lake. Deeper water in the Lake, between 20m and the bottom, is less stratified than near-surface water and Temperature-Salinity (T-S) analysis clearly shows that bottom water enters from across the sill representing a mixture between shelf water just outside the sill and surface water that is exiting the Lake over The Narrows. The T-S diagrams in Figure 4 show two distinct water masses and strong stratification, both in years 2012 and 2013. There is no significant change in water mass distribution between two June months in both year 2012 and 2013. In the lake, the relationship between temperature and salinity is nearly linear, suggesting an almost linear water properties mixing of relative warm and fresh surface water mass, with cold and saline bottom water mass, with mixing across density surfaces.

Tidal flow plays a significant role in the dynamics of an estuary system. The flow in Lake Melville near the sill was mainly tidal, but the non-tidal variations are also frequently quite significant particularly in the Lake farther from the sill. Above 10 m depth, about 18% and 14% of the variances of the velocity time series occurs at the tidal frequencies, at outside and inside mooring locations respectively. Below the 10 meter surface, tidal currents account for about 93% and 54% percent of the total current, shown from outside and inside moorings.

The M2 (semidiurnal) and K1 (diurnal) are the primary tidal constituents at both mooring station. The largest contribution at all depths is from the M2. The inclinations of tidal ellipses represent the degrees the major axes oriented relative to the east. The results show that at both Moorings M1 and M2 the tidal currents were aligned along the axis of Narrows/ Channels boundaries throughout the water column.

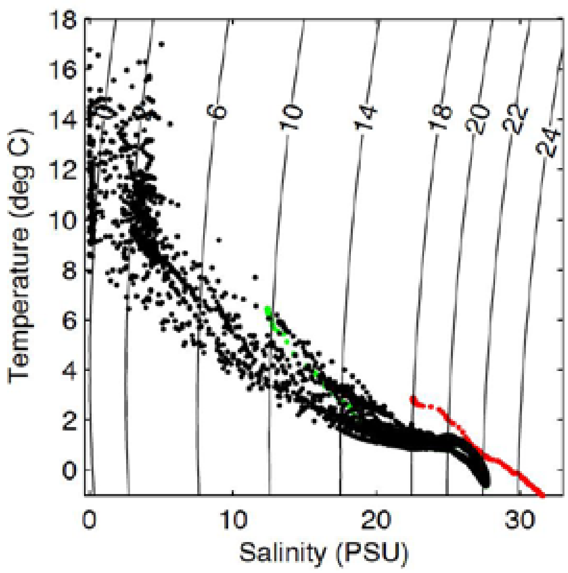

Figure 4. T-S diagrams of CTD data collected along the center of the Lake and Narrows from June to July 2013. The green dots are from M1, inside The Narrows; the red dots are from M2 outside The Narrows.

The small amplitudes of the minor axes indicate a weak cross-channel flow. The ice cover significantly reduced the peak velocities at the surface 30 m layer, from 42 cm/s to 1.8 cm/s at 5 meter depth at M1 station. The arrival of high water level was also delayed, by about 4 hours at M1 station. Below 30 m depth, ice cover could both increase and reduce peak velocity by about 20%, and affect the arrival of the maximum velocity by about 40 minutes at M1 station.

The vertical profiles of the two key tidal constituents without ice present (Figure 5) show that the surface tides are quite strong both inside and outside the sill and that surprisingly the M2 tidal constituent is quite strong even deeper in the water column inside the sill. At 180 m depth, inside the sill, the M2 tidal constituent is roughly 15 cm/s. Not surprisingly the presence of ice does influence the character if the tidal response in the Lake (Figure 6). When ice is present, the surface tidal constituent is greatly reduced while the deeper water tidal response is actually 20-30% stronger. Outside the Lake, there is very little impact of ice on the tidal response.

At station M1, eastward outflowing water was in the upper 20 m, and the compensating westward inflow was at depths below 130 m depth. Outgoing eastward current reached its maximum of about 39 cm/s around the uppermost surface layer and decreased to zero around 20 m depth. Inflow westward current reached a maximum of about 10 cm/s at the 180 m depth. The average speed between 20 m and 130 m was very weak, and between depth 105 to 125 m, speed direction reversed clockwise from northeast to southwest. At station M2, the estuarine circulation is clearly shown, with eastward water in the upper 27 m, and the compensating westward inflow below (Figure 7). Averaged outgoing speed is about 20 cm/s at the surface and gradually increased to its maximum of about 46 cm/s at 10 meter depth. The speed then decreed with depth and changed direction to inward.

Applying Knudsen's relations we were able to calculate the approximate flushing times for the Lake (Figure 8). These results indicate that the flushing time increases through the fall but averages around 190 days. Of course, this is only an average over the water column, in essence an estimate of the mean flushing time. Surface residence times will be much shorter, perhaps just tens of days, given the strong surface currents.

Vertical profiles of Hg, MeHg and DOC are strongly influenced by the stable year-round halocline of Lake Melville (Schartup et al. submitted). Figure 9 shows total Hg and DOC in the Lake Melville water column are enriched in the low salinity surface layer (> 4 pM Hg, >300 µM DOC) compared to the saline bottom waters supplied by the Labrador Sea (<2 pM Hg, <200 µM DOC). This pattern is consistent with inputs from rivers as the major source of total Hg and DOC to Lake Melville, reinforced by strong correlations between aqueous total Hg concentrations, salinity and DOC. The total Hg signal is enhanced by spring snowmelt in June when rivers have significantly higher concentrations (mean 11.4 pM Hg) compared to September (3.6 pM) (Table 1, SI Table 2). Total Hg concentrations at the mouth of the Churchill River (Goose Bay) and in Lake Melville are also

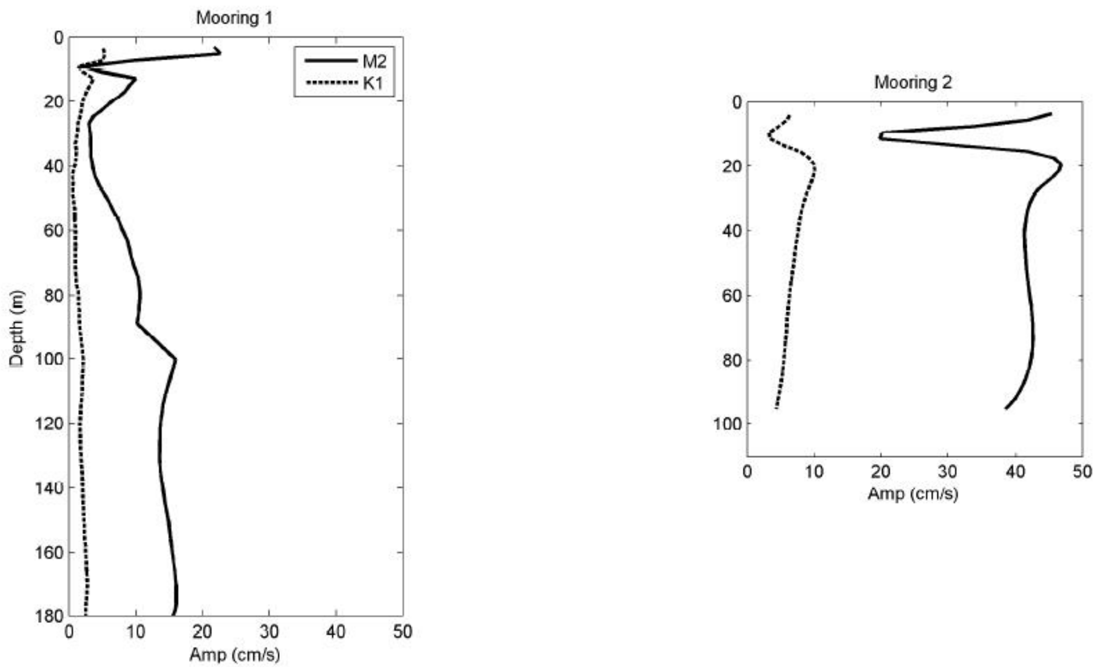

Figure 5. The vertical profiles of the amplitudes of the two primary tidal constituents, the semi-diurnal M2 component and the diurnal K1 component.

significantly higher in June relative to September (t-test, $p<0.01$; Schartup et al. submitted)).

Modelling

The physical oceanographic data collected in the past three years and the knowledge about the Lake Melville dynamics obtained through analysis of these data was essential for development of numerical models of the lake dynamics and climate. Two models were developed which were focused on two different aspects of the physical oceanography of the lake. The first model developed in the PhD project of Zhaoshi Lhu represents detailed picture of the lake circulation, water mass transport and spreading. The second model is focused on the climate of the lake and effects of anthropogenic impact from hydro-power production on its characteristics.

Figure 10 shows results from model simulations of Lake Melville variability during the winter of 1998. Two model experiments are conducted with realistic surface forcing this year, which is one of the warmest year in the record of meteorological observations in the region. The first model experiment is forced with river discharge observed in the period before 1971. The river discharge data applied in the model are monthly averaged observations before 1971. The second experiment is forced with discharge data computed in the same way from observations after 1971.

The major change in the river discharge for these two periods is in the amplitude of seasonal cycle which normally picks in the spring and has minimums in the late autumn and winter. The seasonal cycle is “flattened” after 1971 due to the impact of the Upper Churchill hydro-power facilities which became operational that year. As a result, the winter discharge of Churchill River increased and its spring maximum decreased. The effect of this change reflected in the

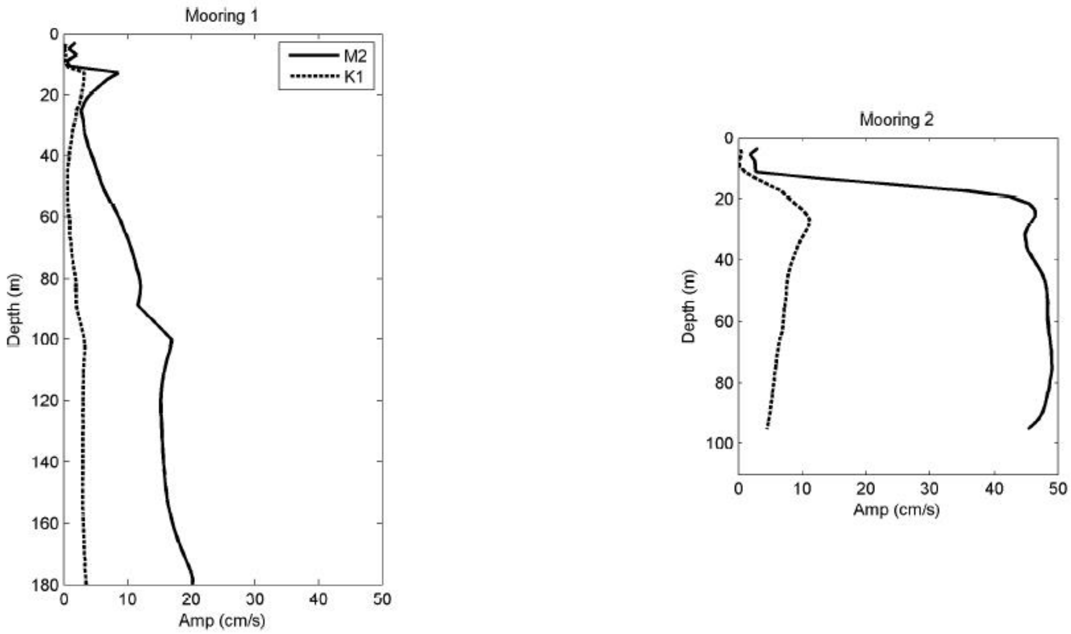

Figure 6. The amplitudes of the two key tidal constituents when ice is present in the Lake.

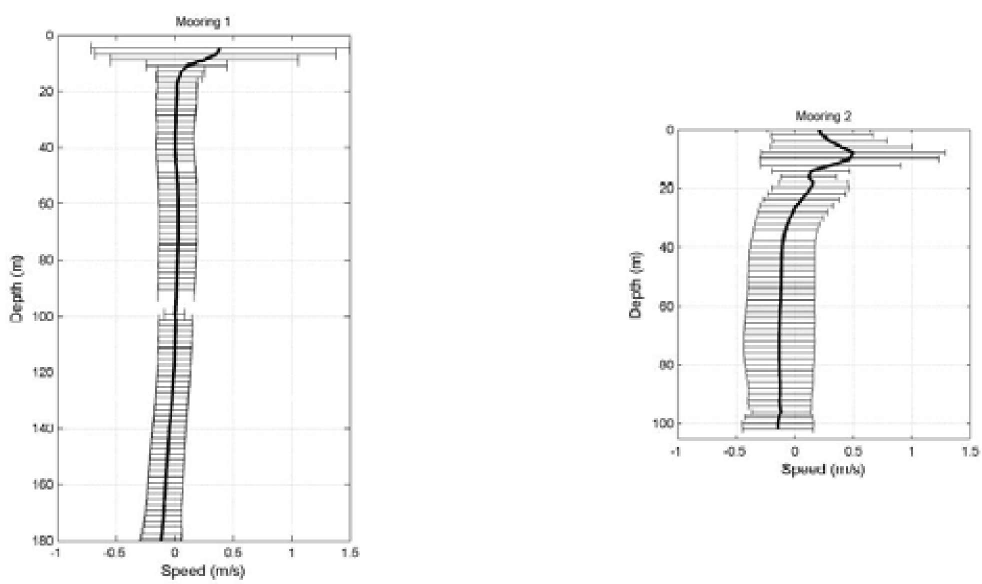

Figure 7. Averaged along-channel currents at the two mooring stations M1 and M2.

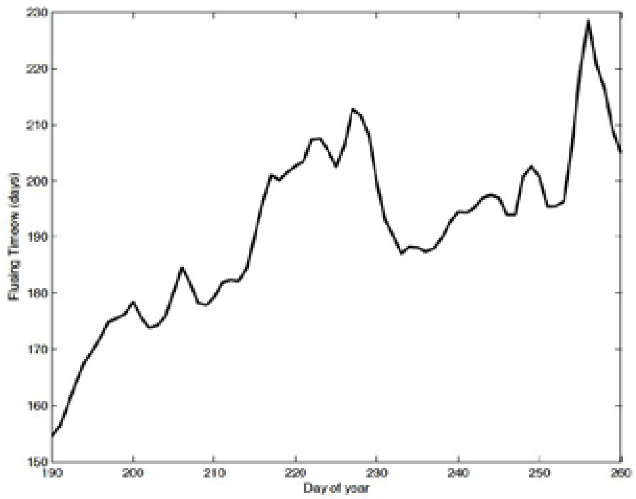

Figure 8. Flushing time for Lake Melville in 2012.

seasonal cycle of the surface salinity in the river discharge area. The latter decreased in winter season with up to 4 psu near the mouth of Churchill River. The upper two panels on Figure 10 demonstrate that the impact of this salinity decrease was strongest in the area of spreading of the river plumes.

The thickness of the mean seasonal sea-ice (left panel in the middle of Figure 10) normally is at a maximum in the area of spreading of the river plume. This is mostly related to the relation between the freezing temperature and salinity. For lower salinity the freezing temperature becomes higher and hence less heat loss is needed in the river plume areas to freeze the lake surface than in the rest of the lake. The decrease in winter salinity in the river plume (upper right panel of Figure 10) in general causes increase of ice-thickness by up to 5 cm (middle right panel Figure 10).

There are, however, two subareas in the region of the spreading of the river plume, where the sea-ice thickness does not increase but actually drastically decreases by up to 18 cm (left middle panel, Figure 10). The first area is just near the river mouth and the second one is further northward upstream the river plume spreading. The ice loss in these areas is caused by dynamical factors which influence the sea-ice drift. The sea-ice velocity is normally relatively strong in this area and near the river mouth (left bottom panel, Figure 10). This high velocity is related to the relatively strong export of sea-ice into the southern part of the lake. The changes in the river discharge intensified this export through intensifying the upper limb of the estuarine circulation during in the winter. This intensification has its greatest impact on ice transport in the two regions. The first one is the area just near the river mouth where changes in sea level and circulation are strongly influenced by any change in the river discharge. The second one is relatively narrow area surrounded by very shallow regions, where the flow is intensified by the "channel" effect of topography. This velocity of sea-ice export into the southern part of the lake is increased by as much as 45% in some areas in this region.

Recent years have seen a number of unusually warm winters in Labrador. Of particular note are the winters of 2009-10 and 2010-11, which respectively rank as the 1st and 4th warmest on record (Finnis and Bell, 2015). Previous research has emphasized that these events were largely a consequence of natural variability, with storm track anomalies associated with the North Atlantic Oscillation (NAO) accounting for much of the warming. However, the NAO remains an unsatisfying representation of these storm track anomalies. Although it suggests warm winters are associated with atmospheric blocking over the North Atlantic (Davini et al., 2012), it provides little insight into the impacts of this blocking on storm activity near Labrador. Furthermore, it is not clear that this connection between the NAO, blocking, and surface temperatures can be used to inform Labrador's climate adaptation efforts, as climate models frequently misrepresent the physical structure of the NAO and Atlantic blocking frequency (Scaife et al., 2010), potentially limiting their ability to simulate realistic extreme warming events. hese shortcomings were addressed using a winter storm climatology developed for the region. Variability in storm frequency, intensity, duration, and source region of systems associated with anomalies in Labrador are examined. Results indicate warm winters are associated with reduced cyclone

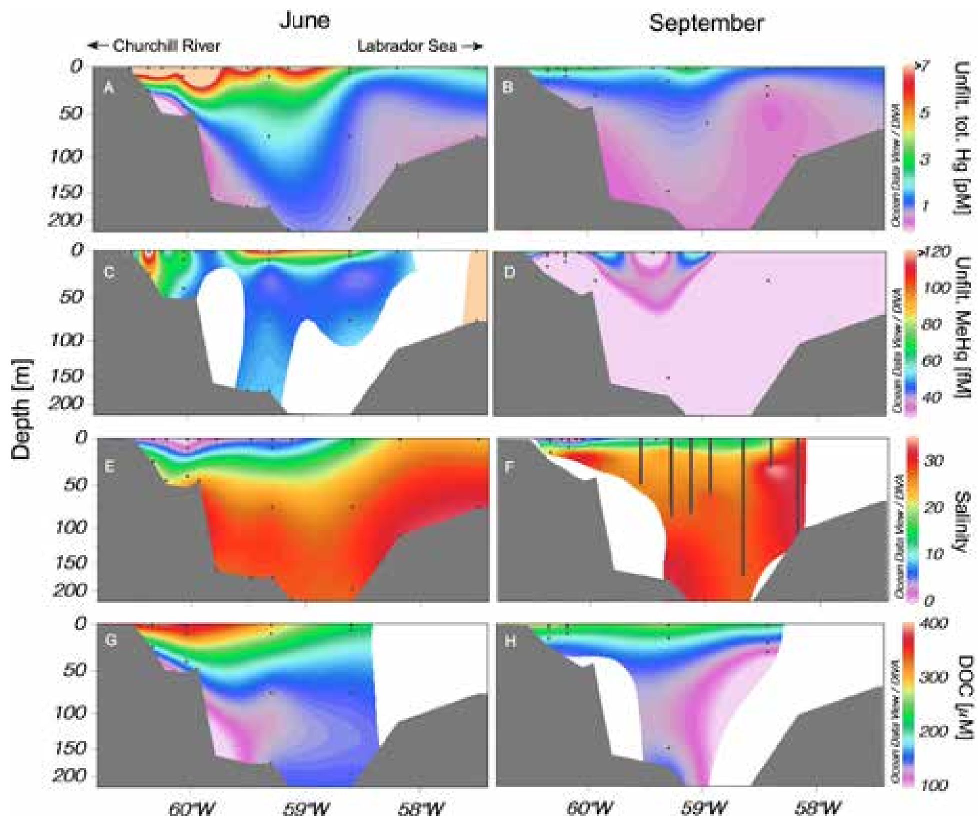

Figure 9. Cross sectional view of total Hg and MeHg concentrations in unfiltered seawater in Lake Melville extending from the freshwater inputs on the left (Churchill River) to outer marine regions (Groswater Bay) that extend into the Labrador Sea. Samples were collected between 31 August and 8 September 2012 and 11-19 June 2013 (from Schartup et al. submitted).

activity in regions expected to cool Labrador, rather than an increase in systems that would warm the region. The result is reduced cold advection from the north/northwest, while warm advection from the south/southeast remains relatively unchanged.

Statistical analysis of extreme winter warming events is also underway to better characterize recent extreme thaw events. Adopting a point process approach to extreme value analysis (Coles, 2001), the frequency, duration, and severity of winter thaws are being examined. Together with the analysis of cyclone activity & warming (Figure 11), these results provide context for interpreting climate change projections for the region, and guidance for climate adaptation planning; by respectively highlighting synoptic conditions associated with extreme winter warming, while providing insight into the unusual nature of these thaws under past climate regimes.

MSc candidate Merran Smith is presently conducting analyses on the variability and changes in Lake Melville sea ice cover. In addition to examining the spatial variability in ice cover across the estuary, Merran is exploring connections between ice change and climate/hydrologic forcing. This work will quantify relative contributions to shifts in ice cover from i) climate change/variability and ii) hydroelectric development (Churchill Falls) on rivers draining into Lake Melville and recent shifts in ice cover reliability. Results will further provide a baseline for comparison in later years, allowing the impacts of the new Muskrat Falls hydroelectric development to be identified once it comes online.

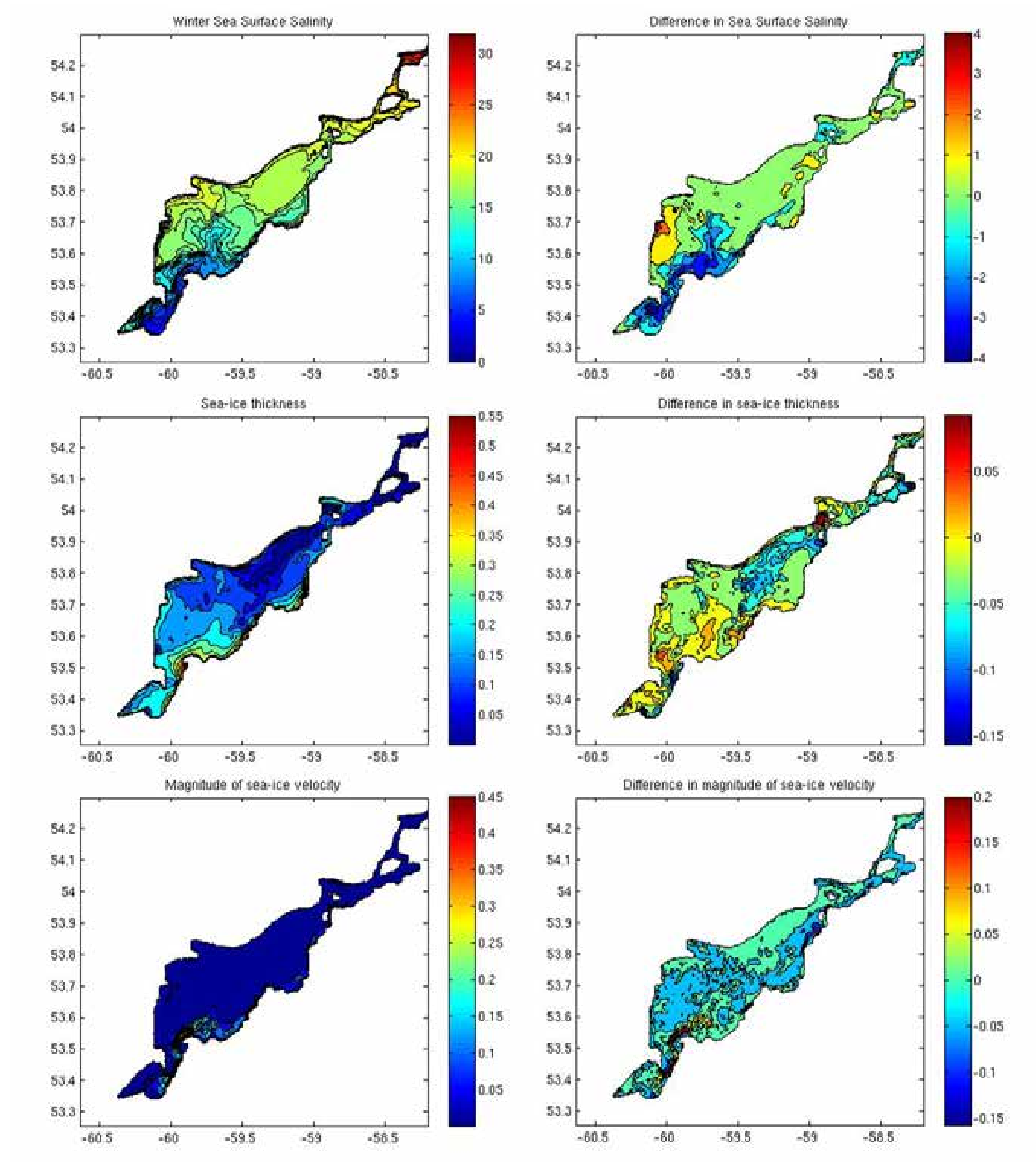

Figure 10. Model simulation of surface characteristics (left panels) of Lake Melville and their differences (right panels) in the two experiments with different river discharge.

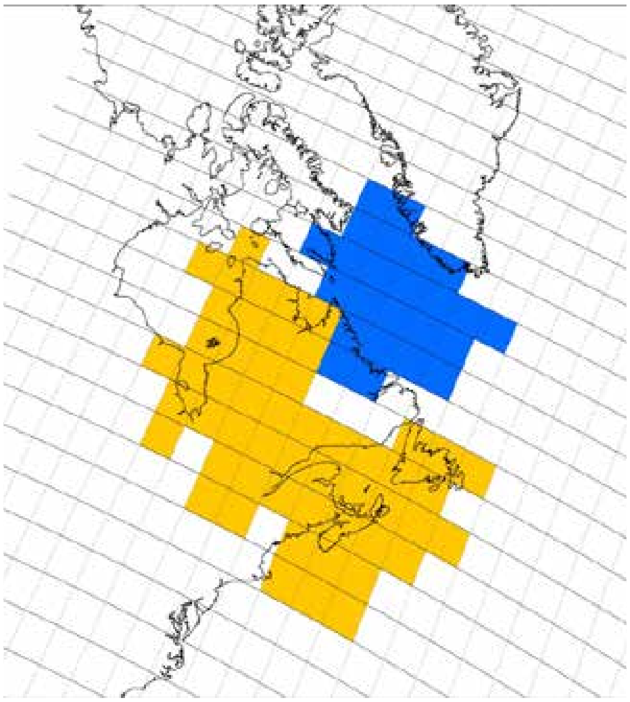

Figure 11. Location of extra-tropical cyclone centres associated with significant warming (yellow) and cooling (blue) in Labrador.

Figure 12 shows the annual mass budget for Hg and MeHg in Lake Melville constructed from a compilation of field measurements (Schartup et al. submitted), following methods described in Sunderland et al. (2012). Rivers are the dominant source of total Hg inputs (457 mol a^{-1}) followed by direct atmospheric deposition (51 mol a^{-1}). Tidal inflow is a large gross source of Hg to the estuary (703 mol a^{-1}) but outflow results in a net loss to the Labrador Sea. Moreover, advective inflow of Hg through tidal exchange is mainly confined to the saline bottom waters of the estuary due to strong stratification, while most biological activity and methylation occurs in the upper 50 meters of the water column (Figure 9; Schartup et al. submitted).

Water column production of MeHg is the largest net source in Lake Melville (9 mol a^{-1}), closely followed by direct inputs from rivers (5 mol a^{-1}) (Figure 12A). Gross inputs of MeHg through tidal exchange are large but Lake Melville is a net source (8 mol yr^{-1}) to the Labrador Sea, similar to the dynamics of inorganic Hg. By contrast to what has been postulated for many mid-latitude estuaries, benthic sediment in Lake Melville is a net sink not a source of MeHg for the estuarine water column. Although active methylation of HgII in the sediment produces 23 mol MeHg yr^{-1}, most is demethylated rather than transported to the overlying water column through diffusion or resuspension (1.1 mol/year).

Monitoring

Ten sentinel benthic monitoring stations were established in 2013-14 throughout the Lake Melville basin. Sixty-seven box cores were recovered at these stations for faunal, chemical and sediment analyses. Initially, samples from seven stations were analysed for species richness and tests for homogeneity within and between stations. One hundred fifty-five species were identified at these seven stations. Stations differed significantly in number of species present from a low near the mouth of the Churchill River (GB3; Upper lake Melville) to a high near the mouth of the estuary (CAR, BW1; Figure 13). There was no significant difference in species abundance and composition between replicates (up to 5) at each station.

The SmartICE project established a community sea-ice thickness station (C-SITS) near North West River in Upper lake Melville to monitor weekly sea ice thickness at a location known to be unreliable for ice. Sea ice conditions were mapped by local sea ice specialists from North West River and their observations were used to validate classification of radar satellite imagery of the region (Figure 14).

DISCUSSION

Modern sediment accumulation rates, and thus the potential sedimentary sink for mercury, vary widely within the Lake Melville system. Proximity to rivers mouths, as reflected in (spring) surface water

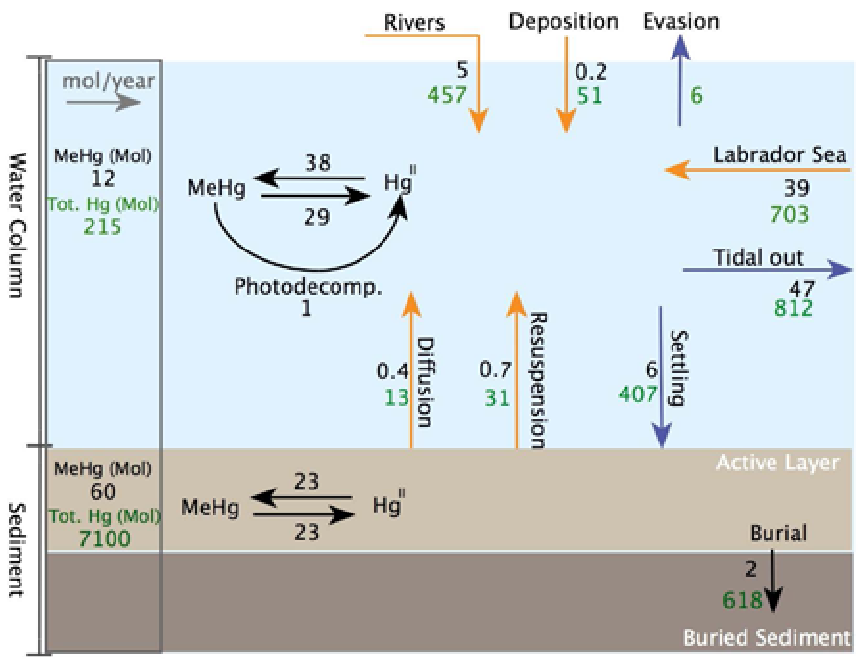

Figure 12. Empirically constrained annual mass budget for total Hg and MeHg in Lake Melville(from Schartup et al. submitted). Mass flow rates are shown as mol Hg a^{-1} and reservoirs are given in moles. Orange arrows represent external sources of MeHg and total Hg to the water column and blue arrows represent losses.

salinity and secondarily in water depth, appears to be a primary factor in controlling accumulation rates. Preliminary particle size distribution data suggest an eastward fining from Goose Bay across Lake Melville, accompanied by an increase in organic carbon concentrations. Thus, it appears Goose Bay acts as a sediment trap for coarser inorganic materials while finer, more organic-rich materials are transported preferentially eastward and gradually deposited across the Lake. This trend may be of significance for interpreting mercury deposition patterns. However, marine primary production also contributes to the overall flux of organic matter to the sea floor within the Lake. Stable carbon isotope ratios ($\delta^{13}C$) of surface sediments are being measured to allow quantification of the relative contributions of terrestrial and marine carbon across Lake Melville and provide a basis for assessing the relationships of each carbon type to mercury deposition and capture.

Once the analyses of sediment cores collected in 2014 are completed, a more robust understanding of the mechanisms involved in the transfer and deposition of material and the relationships with mercury capture can be achieved. The sediment core data collected in this study will be used together with previously published literature to construct a contemporary sediment and organic carbon budget for the Lake Melville system. This budget will provide a basis for evaluating processes that are sensitive to future hydrological and climatic changes, while at the same understanding processes that play an important role in mercury transport and distribution. Dated sediment cores will also be used to evaluate the evidence for past change in sediment and terrestrial organic matter supply to the system.

The data collected on water column properties in this study point to the complex interplay of river runoff, inflow from Groswater Bay, and vertical mixing in supplying nutrients to surface waters to support

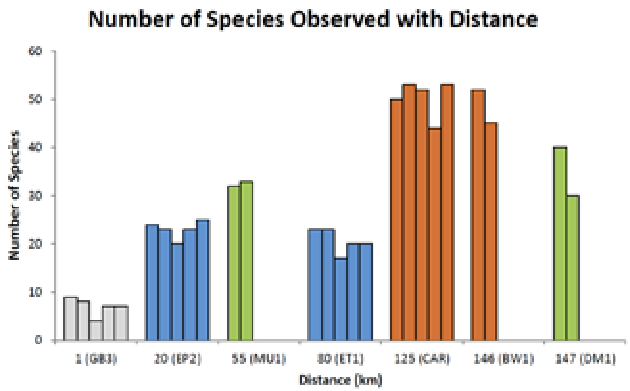

Figure 13. Graph of number of observed species with distance from the mouth of the Churchill River, color coded for statistical similarity at α=0.05.

primary production. The results also point to possible light limitation of phytoplankton biomass, at least at certain times of the year. Short residence times of surface waters, especially during June, when the data were collected, may post a further constraint on the phytoplankton biomass observed in the system. The recent measurements represent some of the first data on water quality and phytoplankton biomass collected in the system in decades. In part, it helps update the available baseline data. Furthermore, it provides important context for assessing the possible contribution of primary production to the total inputs of sediment and organic carbon to the system, as required for budget estimates.

The physical oceanography program has led to direct and new observations of the circulation and dynamics of Lake Melville. The numerical modelling work enabled integration of the observations and exploration of the sensitivity of the transport and sea-ice dynamics to climate forcing and changes in freshwater runoff. The observations clearly showed the character of the estuarine circulation of the Lake and the role of sea-ice in modifying the wind forced coupling of the circulation and the tidal dynamics. The direct observations and the models were used to provide new estimates of the residence time for water in the lake and the exchange characteristics of the deep water of the Lake. The numerical models enabled exploration of the tidal dynamics throughout the Lake and the response of sea-ice characteristics to the changing forcing conditions in the Lake.

We measured a large (14 fold) increase in MeHg concentrations in inland cores collected from dry soils in the planned reservoir region of the Muskrat Falls hydroelectric project and smaller increases in cores collected near the river shore where occasional flooding already occurs (Schartup et al. submitted). In the nearshore cores a small peak occurs three hours after saturation and no further increase in MeHg is seen.

The majority of the planned flooded region (41 km^2) will be inland soils, in some cases covered by vegetation and trees (Nalcor Energy 2009). Thus, our experimental measurements of MeHg increases represent a lower bound for increases that may be expected following flooding of the lower Churchill River in 2017.Our results also show that soils from this region have the capacity to sustain MeHg production over long time periods once flooded (Schartup et al. submitted).

Prior research in the Experimental Lakes Area of Canada showed 40-fold increases in aqueous MeHg concentrations following large scale flooding and increased biological concentrations that persisted for more than a decade (St. Louis et al. 2014). Flooding associated with creation of a hydroelectric reservoir at Muskrat Falls can thus be expected to substantially enhance MeHg concentrations in the main tributary of Lake Melville, which is already a large direct source of MeHg (Schartup et al. submitted).

Climate driven changes are increasing freshwater discharges from Arctic rivers and sea-ice melt, increasing stratification of many marine regions (Wassmann 2011). Prior studies in the Arctic Ocean note elevated MeHg concentrations in the stratified surface waters affected by ice melt (Lehnherr et al. 2011). Here we suggest that MeHg bioaccumulation is enhanced in stratified marine waters (Schartup et al. submitted). Bacterial activity and associated water column MeHg production, phytoplankton and

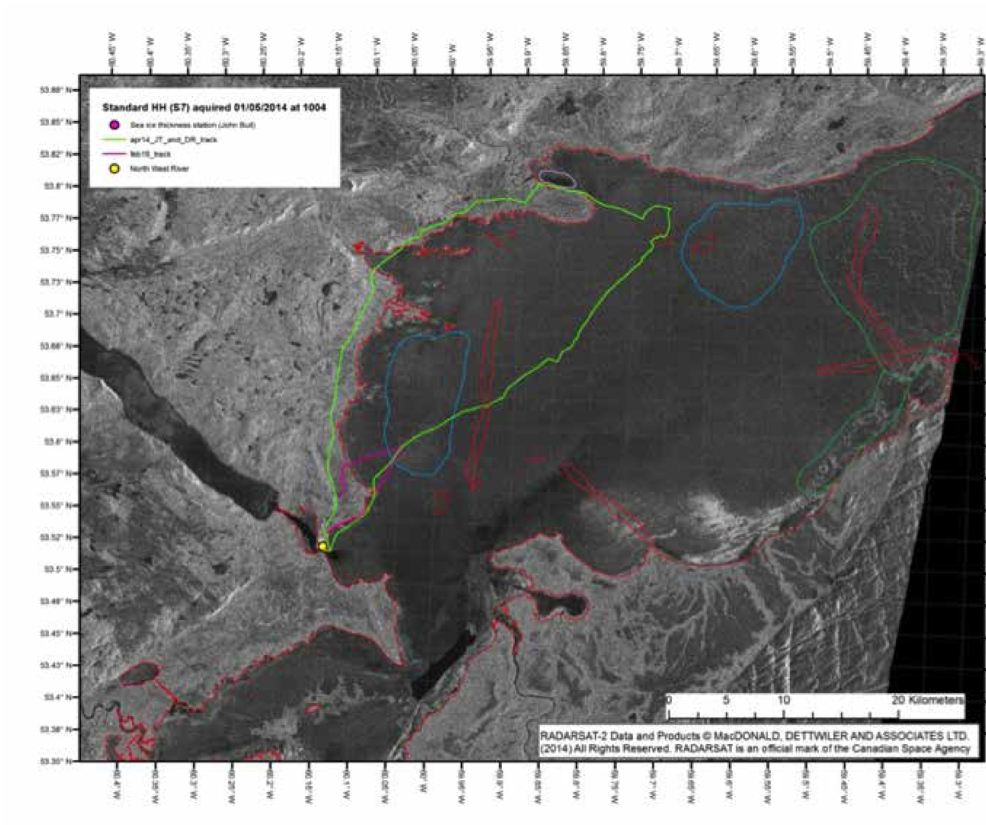

Figure 14. Map showing tracks of SmartICE operators (colour lines) as they travel on the sea ice to observe conditions and ice types for validation of satellite imagery (map courtesy of B. Wood).

zooplankton are concentrated in a more vertically restricted zone in stratified systems. This can enhance MeHg exposures of plankton and increase trophic structure leading to higher biomagnification.

CONCLUSION

The two main goals of Lake Melville: Avativut, Kanuittailinnivut are: 1) to establish baseline conditions for Inuit health, community wellbeing and ecosystem function/integrity in Lake Melville prior to any Lower Churchill hydroelectric development, and 2) to develop the science for monitoring the downstream effects of hydroelectric development on a subarctic estuary and coastal Inuit communities in the context of ongoing climate change impacts. Research thus far demonstrates that mixing and exchange dynamics are tidally forced (diurnal and semi-diurnal tides) and strongly influenced by the freshwater river discharge, especially from the Churchill River, at the west end of Lake Melville. Our studies point to the complex interplay of river runoff, inflow from Groswater Bay, and vertical mixing in supplying nutrients to surface waters to support primary production in Lake Melville. Short residence times of summer surface waters may indicate a further constraint on the phytoplankton biomass observed in the system.

At a climatic level, the impacts of anthropogenic climate change at the end of the last century were largely obscured by slow-varying (low frequency) variability in Labrador, which over the last decade or so has enhanced regional warming. Climate changes are most apparent in winter when in some years this warming has included prolonged thaw events (e.g.,

2009/10, 2010/11). These warm winter events are driven by variations in local atmospheric circulation; the negative phase of the North Atlantic Oscillation captures some of this variability, but remains an imperfect predictor of Labrador winter temperatures.

We conclude that increased MeHg concentrations in the Lower Churchill River are likely to increase concentrations and biological uptake of MeHg throughout the low salinity, biologically active surface waters of Lake Melville (Schartup et al. submitted). We measured a 14-fold increase in MeHg concentrations in flooded dry soils in the planned reservoir region of the Muskrat Falls hydroelectric project and show that soils from this region have the capacity to sustain MeHg production over long time periods once flooded. Concluding work is focusing on integration and coupling of biophysical and human health systems. A dietary survey of Inuit from the Lake Melville region was combined in 2014 with the optional collection of a hair sample to evaluate a baseline exposure model. Mercury analyses are ongoing. A final major report involving baseline establishment, modeling and state of the art monitoring with associated communication materials will be published in 2015.

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FOOD SECURITY, ICE, CLIMATE AND COMMUNITY HEALTH: CLIMATE CHANGE IMPACTS ON TRADITIONAL FOOD SECURITY IN CANADIAN INUIT COMMUNITIES

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ABSTRACT

Traditional/country foods are critical resources for physical, as well as mental, social and economic health of individuals and communities across the Arctic. Despite this, shifts in traditional/country food consumption have been taking place over the past 15 - 20 years related to a variety of changes in northern ecological, social, political and economic systems. Those related to ecological shifts have been in part previously associated with reduced confidence in food safety due to identified threats from environmental contaminants such as mercury and PCBs, and more recently the changes in species availability and accessibility due to shifting climatic conditions. Specifically, climate-related changes and variability in the North have been associated with changes in animal, fish and plant population health and distribution, while changes in ice, snow, precipitation regimes, and other environmental factors have the potential to influence human travel and transportation in the North, and thus Inuit access to these wildlife resources. As such, climate change and variability has the potential to influence nutrition and health status among Inuit via impacts on aspects (availability, accessibility and quality) of traditional/country food security. Earlier phases of this project identified both positive and negative changes in the traditional/country food harvest of Inuit communities in relation to changes and variability in climatic conditions. It was documented that environmental changes are already having impacts on both the availability of wildlife species and hunters' access to them in all regions studied. In some regions, Inuit have reported some influence of climate and environmental change on wildlife access and availability in comparison with the same hunting season in previous years. However, the impacts are not homogenous among all hunters and communities and both individuals and households show differential ability to adapt successfully. Factors such as access to economic resources and equipment, experience, and the nature of the adaptive strategy used appear to influence the success of hunter adaptations. Yet, our current commonly used assessment tools looking at household food insecurity in Inuit regions do not represent this complexity well. As a result, we have decreasing confidence in the accuracy of results from these tools in capturing the full nature of the reality of Inuit food issues. This project has studied these issues through a variety of sub projects at the national, regional and community level including: a more holistic characterization of the Inuit food system through mixed quantitative-qualitative modeling approaches; methods to link and reconcile the contradictions between wildlife management and household food access; the review and development of new rapid assessment tools; the support of community-led food assessment processes and the development, implementation and evaluation of community-led interventions; the characterization of household food 'needs' and the impact of access to community food support mechanisms, such as community freezers, in addressing these needs.

KEY MESSAGES

- Food security is significantly influenced by community-specific factors and the variability of levels of food insecurity within a region must be considered in order to support effective and well-targeted action.
- Estimates of food insecurity at the community scale in Nunavik, using the Qanuippitaa dataset (collected in 2004), range between 9% and 52% and are associated with high levels of uncertainty in presence of low sample sizes.
- Estimates of food insecurity in Nunatsiavut range between 16 and 72% based on recent surveys conducted in the coastal communities under this project.
- A scenario approach to discussing the relationships between wildlife resources and Inuit household food security and the adaptations to changes in food access is an effective way in which to engage decision makers from different sectors on this topic.
- A simplified tool for assessing Inuit household food security has been developed based on the Inuit Health Survey dataset.
- Community freezers are reported to be effective mechanisms through which to support household food security. An evaluation of the freezer program in Paulatuk is being completed to assess its impact on food security in that community.
- A participatory food pricing method has been developed in the ISR, based on the FoodArc method.

OBJECTIVES

General Objectives

- Gain a better understanding of Inuit food security, the role of environmental and socio-economic factors and their variability in household food security status;
- Assess role of key adaptation/intervention strategies to address environmental change pressures on household food security in remote Inuit communities;
- To develop a quantitative ecosystem-based modeling framework integrating determinants of arctic food security, from the regional to the local scale, to support future decision-making;
- Help support the creation of a national mechanism for information exchange and learning among regions on this topic (Inuit Food Security working group through cooperation with ITK) and inform them with state of knowledge on Inuit food security issues and strategies;
- Develop new tools and methods for assessing and investigating Inuit food security that better represent the nature of food challenges and the food system in Inuit communitiesRegion specific objectives.

Nunavik

- Develop standardized protocols to characterize and assess vulnerability and adaptation for traditional food security in Inuit communities;
- Identify and evaluate factors influencing household food security status (including climate and environmental change and a series of socio-demographic variables) and their distribution in Nunavik communities.

Nunatsiavut

- Determine the prevalence of factors influencing vulnerability and adaptive capacity for food security impacts of climate change;
- Assess the role of environmental (and other) factors in influences individuals' use of a key food

security adaptation mechanism (e.g. community freezer) in one community (Nain and Hopedale);

- Support communities in identifying, assessing and addressing local food security issues and designing, implementing and evaluating community-based food interventions to address them.

Inuvialuit Settlement Region

- Determine traditional food species key to both nutritional and cultural security and identify means to balance sustainable harvesting, nutrition and cultural use, if this becomes necessary;
- Determine the local and regional parameters of adaptation that are acceptable and viable among Inuvialuit Settlement Region communities;
- Develop detailed adaptation planning to allow the communities of the Inuvialuit Settlement Region to maintain food and cultural security;
- Incorporate the risk and benefits of traditional foods into planning for food security;
- Scale adaptation planning from the local to the regional level;
- Determine the current state and future prospects for cultural food security in the Inuvialuit Settlement Region. In the long term it will facilitate community adaptation planning and assist the communities in developing region wide adaptation planning for the maintenance of traditional food security across all the communities in the ISR;
- Implement the ISR Food Security Working Group (ISR FSWG), by defining and adopting its membership, mandate and terms of reference;
- Conduct a qualitative assessment of existing food security and harvester support programs, to identify additional programs, opportunities and barriers to program effectiveness, and program gaps;
- Document community freezer initiatives in the ISR, to identify the opportunities and barriers to program effectiveness;
- To develop a methodology for participatory food costing in the ISR.

INTRODUCTION

Despite the recognized importance of traditional/country food as a critical resource for the health and well-being of northern populations (Donaldson et al., 2010; Van Oostdam et al., 2005) significant shifts in their consumption have been taking place over the past 15 – 20 years at the same time as dramatic changes in northern climatic, ecological, social, political and economic aspects. The changes related to ecological shifts have been in part associated with reduced confidence in food safety due to identified threats from environmental contaminants such as mercury and PCBs (e.g. Donaldson et al., 2010; VanOostdam et al., 2005), and more recently the changes in species availability and accessibility due to shifting climatic conditions (e.g. CCA, 2014; Furgal, 2008; Ford and Beaumier, 2010; Guyot et al., 2006; Berner et al., 2005; Chan et al., 2006). Specifically, climate-related changes and variability in the North have been associated with changes in the diversity and distribution of the biotope (game, fish and and botanic) (Prowse et al., 2009; Wrona et al., 2005; Loeng, 2005; Callaghan, 2005). Changes in ice conditions, snow distribution, and rainfall frequencies and other climatic factors have the potential to influence human travel and transportation in the North, and thus Inuit access to their wildlife resources (Tremblay et al., 2006; Furgal and Seguin, 2006; Furgal 2008). As such, climate change and variability have the potential to impact nutrition and health status in the Inuit population through changes in traditional/country food availability, accessibility and quality.

Food security in Inuit regions of the North is already at alarming rates (CCA, 2014; Rosol et al., 2012; Egeland et al., 2011) and therefore understanding the nature and distribution of the issue and the pressures placed on this public health issue by environmental and other forms of change is important. Previously under this project we have identified both positive and negative changes in the traditional/country food harvest in five Inuit communities in relation to changes and variability in climatic conditions. It has been documented that environmental changes are already having impacts on both the availability of wildlife species and hunters' access to them in all regions studied (Nunavik and Nunavut, e.g. Alain, 2008). Additionally, during the Nunavik Regional Inuit Health survey, respondents reported some influence of climate and environmental change on wildlife access and availability in comparison with the same hunting season in previous years (Furgal and Rochette, 2007).

However, as documented in earlier phases of this project, the impacts are not homogenous among individuals (e.g. hunters) in the same community or between households. Variability in adaptive capacity is evident representative of the reality of Inuit communities today. Factors such as access to economic resources and equipment, long-term experience, and the nature of the adaptive strategy employed seem to influence the success of hunter adaptations. Therefore, it is important to study further these factors at different levels of organization in Inuit regions.

Through the conduct of research and knowledge translation activities at the national (Projects 1,5) and regional scales in Nunatsiavut (Project 2), Nunavik (Project 3), and the Inuvialuit Settlement Region (Projects 4-7) we have explored these aspects of this critical public health issue.

ACTIVITIES

Project 1: Integrated model of arctic food security-identifying and acquiring data to transform our conceptual framework into a viable tool to enhance decision making (all regions)

In 2014-15 we continued circulating requests for data access from existing projects generating data of importance to the issue of food security in Inuit communities. This included requests for environmental and biological data related to resource availability and accessibility throughout the North. Additionally, we consulted and developed a partnership with CHARS on the issue of large scale integrated modeling on food security and the influence of various factors in the Arctic based on their interest in the topic and potential capacity to support the development of such modeling efforts. Finally, we attended and presented at Arctic workshops and meetings to present on the idea of integrated modeling and consult with Arctic researchers to seek interest in participation on data integration for food security modeling.

Project 2: Factors influencing food security in Nunavik

For obvious logistical (physical and financial constraints on sampling effort) and statistical reasons (large coefficient of variation), levels of household food insecurity indicators are often reported at a regional level only and based upon a limited number of samples. The rate reported for the region of Nunavik is no exception. The 2004 Qanuippitaa? How Are We? public health survey conducted in the 14 communities in that region gathered data from a total sample size of 2089 households, and reported an overall household food insecurity rate of 24% (i.e. observed proportion of total number of Nunavik households sampled reporting having lacked food at least once during the month preceding the survey). Because reported rates of food insecurity were not common at the time in Inuit regions, such a study provided an invaluable comparison point with other Canadian regions and supported public heath recommendations and initiatives. Nonetheless, one recurrent critique of the dataset is that this food insecurity knowledge does not account for potential community variability and socio-cultural and economic differences between communities. As a result, the dataset is not looked at as having significant value in considering action and responses at the community scale. In order to respond to this major limitation we reinvestigated the 2004 Qanuippitaa? How Are We? household public health data at a community level in 2014-15 in order to provide appropriate knowledge to support public health policy making. We adopted a Bayesian statistical framework which permitted us to easily compute and present community-specific household food insecurity probabilities along with the associated level of uncertainty. The uncertainty was represented by upper and lower boundaries providing the range of 95% of the distribution of possible values for a given community while considering the random sampling process used in the survey.

In 2014-15 we completed the initial analysis of this dataset using this approach and presented the results to the Nunavik Nutrition and Health Committee (NNHC) and Regional Health Board (NRBHSS) in Kuujjuaq. As well, we participated in a half day workshop on this topic with the NNHC and NRBHSS to help increase understanding the status of food security knowledge in the region in support of the development of a regional food strategy in the future.

Project 3: Understanding Food Security Rates in Nunatsiavut

In 2014-15 we completed four community-wide household food security and needs surveys in the communities of Nain, Hopedale, Makkovik, and Postville, Nunatsiavut. In order to complete these surveys, community surveyors were identified, hired, trained and employed for data collection. Through collaboration with our partners in each of the Inuit Community Governments, the Environment Division of the Nunatsiavut Government, the Food Security Network of Newfoundland and Labrador, and through cooperative funding from the Canadian High Arctic Research Station, Aboriginal Affairs and Northern Development Canada, and the Public Health Agency of Canada we have been able to develop a comprehensive database of community food security rates in this region at the community scale. Through collaboration with the researchers at the University of Guelph and McGill University and their data for the community of Rigolet, we have community specific on this issue for the first time in a complete Inuit region in the Canadian Arctic. Data analysis has been ongoing and preliminary results communication has taken place to each of the coastal communities. Wider public release of these data and the study results is planned for this spring. Additionally, we continued to pursue access to the Inuit Health Survey dataset for this region to re-analyse the data on food security from the coastal communities using the methods developed for Nunavik in Project 2. The request for access to this data is ongoing.

Projects 4-7

Projects 4-7 were progressed, in part, through the conduct of a 2-day workshop on May 13-14, 2014 gathering participants from all ISR communities to discuss ongoing food security research projects and identify research priorities, based on the priorities discussed during a previous regional meeting in July 2012 (Fillion et al., 2014). Representatives working in both wildlife and environment (e.g., HTCs, Community Corporations, Inuvialuit Joint Council) and human health and nutrition (e.g., nutrition, environmental health, social work) were brought together to share information about food security. The aim was to think about how we can work towards improved food security in a way that supports both environmental health and human health over the long term. This workshop was part of a long-term relationship between Dr. Laurie Chan's research team and members of the ISR, who have been working together to address issues around country foods, food security, diet and health for many years. This workshop was an opportunity to work on an existing project (Project 4) and three newer projects related to food security (Projects 5, 6, 7).

Tiff-Annie Kenny and Myriam Fillion visited the ISR again in November and December, in order to further develop the projects discussed during the May workshop. They visited 5 of the 6 communities to initiate the participatory food-costing project, and Paulatuk to initiate the community freezer evaluation.

Project-specific activities (4-7)

Project 4: Reconciling food security and wildlife protection needs (ISR)

The purpose of this project is to develop a framework and model to relate issues of Inuit health, access to country food, and diet, within a forum that is mutually relevant to wildlife managers. This work represents, therefore, an effort to bring together wildlife conservation, into the broader discourse of Inuit diet, nutrition and food security, and, likewise, situate issues of Inuit diet, nutrition and health, within the broader context of harvest and wildlife management.

We have characterized regional country food consumption and established baseline determinations of country food harvest for selected species of wildlife (caribou, ringed seal, and beluga), in the five regions of Inuit Health Survey (2007-2008). These results were presented at the 2013 ArcticNet Annual Scientific Meeting, and are summarized in a manuscript (Kenny, T.-A., Egeland, G., Chan, H.M. Estimation of Harvest Need of Wildlife for Consumption among Inuit In The Canadian Arctic). The manuscript is complete and pending review from the IHS Steering Committee.

Results of this work were also presented at a regional workshop in the Inuvialuit Settlement Region (Inuvik, May 2014) attended by members of the wildlife management and health sectors, and community representatives from Hunters and Trappers Committees and Community Corporations. The regional workshop provided an opportunity for participants to discuss strategies and research priorities to promote the sustainable use of country food to support food security in the Inuvialuit Settlement Region. At the consent of participants, focus groups from the workshop were audio-recorded and will be transcribed. Results from the workshop focus group session will be prepared in a manuscript (anticipated submission: summer 2015).

In relation to this initiative, we conducted a systematic review of literature to examine the extent, range and nature of research at the intersection of wildlife and food security in the Canadian Arctic. Through this work, we have identified commonalities between these distinct, yet related, fields of interest and are working to develop an integrative framework to identify how wildlife management and health promotion may best co-adapt to meet the needs of Inuit communities within the context of environmental change. The results of this review are being prepared in a manuscript (Kenny, T.-A., Fillion, M., Chan, H.M. 2014. Reconciling Indigenous Food Security & Wildlife Management in the Canadian Arctic) to be submitted in spring 2015.

Project 5: Developing a multidimensional instrument for a valid assessment of food security in the Canadian Inuit context (all regions)

The food security instrument tool proposed in the 2013 ArcticNet report was further developed in 2014. In 2013, in an initial phase, we developed a quick and valid screening tool for Inuit household food insecurity from data of the IHS. In a second phase, socio-cultural dimensions were incorporated, using a multivariate approach. In 2014, sensitivity, specificity and convergent validity tests will be carried out. A manuscript has been written and is now under revision by the IHS National Steering Committee (Philibert, A., Fillion, M. and Chan, H. M. (2014) "Development of a New Assessment Tool for Food Security for the Canadian Inuit Population", in revision).

Project 6: Documenting and evaluating food security interventions in the ISR: the Paulatuk community freezer case study (ISR)

During an ISR regional workshop (Inuvik, May 2014), participants talked about a number of food security initiatives available in the region, but were curious to know what were all the programs available in the ISR. They also mentioned that some programs were not well known, making them difficult to access or to judge their effectiveness.

Community freezers have shown to play a role in community food security. A recent study in Nain (Nunatsiavut), showed that the community freezer was a key element for households facing food insecurity (Organ, 2012). During the regional workshop of May 2014, participants highlighted community freezers as a focal area for further consideration in research and intervention projects in the ISR. Participants mentioned that community freezers could increase the access to country food all year long. Since communities from the ISR have had different experiences with community freezers, participants encouraged the documentation and evaluation of elements of success and non-success to inform the development of future initiatives in the region.

We are developing a holistic framework to document and evaluate past and current local-scale food security interventions in the ISR, starting with evaluation of the Paulatuk community freezer as a case study. A participatory evaluation methodology is being followed (Brownson et al., 2011; NCCAH, 2013), with active engagement of regional and local stakeholders, including the Inuvialuit Regional Corporation, Community Corporations, Hunters and Trappers Committees and community members. In a first phase (Fall 2014), we are worked with key informants to identify culturally relevant evaluation questions and outcome indicators. In a second phase (Winter 2015), we will collect the data to complete the evaluation. This participatory evaluation process will provide a mixed qualitative and quantitative understanding of community freezer initiatives in the ISR, identifying elements of success and non-success, to improve decision-making and design of future food security interventions.

Project 7: Developing a participatory food costing methodology to accompany food prices at the local level (ISR)

The Inuvialuit Settlement Region (ISR) includes one road-accessible community and five plane-accessible communities. The Inuit Health Survey 2007-2008 found that 33% of households in the ISR were moderately food insecure, with 13% experiencing severe food insecurity. Despite access in 5 of 6 communities to a federally administered food subsidy program, there is concern within the region that food is unjustly expensive. While it is mandatory for food retailers to publish quarterly food price reports in remote communities, residents have expressed concern that these reports lack transparency and that the “voice” of communities is neither being heard, nor heeded, on the issue of food prices. Participatory food costing is an established methodology to gathering food prices, and yields independent, internally-generated food price data at the community level and empowers community members to contribute directly to the resolution of an important local food system issue.

The project has been developed in a participatory manner following a 2-day food security workshop held in Inuvik in May 2014 which involved representation from all ISR communities, and the health, education and wildlife sectors. The project will build on local expertise and strengthen capacity in ISR communities by hiring and training community members in food-costing methodologies. The project will consist of two data collection points, one in the fall of 2014 and the other in early spring of 2015. The list of food items to be included in the costing project will be established in consultation with the ISR FSWG to capture the realities of healthy eating in ISR communities, and to reflect the dietary habits of Inuit reported in the 2007-2008 Inuit Health Survey. Researchers will coordinate and convene with other food costing initiatives across the north, including Paying for Nutrition in Northern Canada and Food Secure Canada, to advance the development of a culturally appropriate, northern food costing methodology, and facilitate the inter-regional comparability of food price results. A strategy for knowledge translation and results dissemination will be developed in collaboration with the local stakeholders to render results from the study, accessible and meaningful, to community members.

RESULTS

Project 1: Integrated model of arctic food security: identifying and acquiring data to transform our conceptual framework into a viable tool to enhance decision making (all regions)

After over two years of participation in networking events, collaboration and discussion with government agencies, stakeholders and academics, we have been able to strengthen applied conclusions on transforming our conceptual holistic model of arctic food security to support policy making. The first result is solely logistical. Implementing an applied tool for policy makers supported by a large range of diverse datasets requires significant human resources as well as political support. The second result pertains to questioning the pertinence of such a holistic project when initiated by academics rather than a government agency or organization. On a practical side, academics are not tasked or empowered with the legal authority often needed to gain data access for such activities in short time when research and analysis is ongoing. In fact, in such applied modeling contexts, there may very well be a conflict between the interests of serving the public or decision makers needing early and easy access to synthesized data in order to support decisions, and the needs of the researcher to protect access to the data for their own publishing and ongoing analytical priorities and needs. This is particularly the case when the research being conducted is not exclusively being undertaken for the purposes of far reaching modeling activities regardless of whether or not they may support decision or policy maker's needs. There is a need for a better understanding among scientists, policy makers and stakeholders of the potential roles and their value, played by different actors involved in the data and knowledge generation, dissemination and public decision making chain in this regard. On the basis of these statements we developed practical recommendations to address arctic food security policy making in the context of climate change and human development, the most important being the importance of driving applied global change research by stakeholders' needs and desired outcomes for adaptation. We are currently working with Dr. McLennan, collaborator, from the Canadian High Arctic Research Station (CHARS) to properly establish an expert network and working group under the auspices of CHARS to facilitate these issues of data access and sharing in relation to integrated modeling for Arctic issues, such as food security, in the future.

Project 2: Factors influencing food security in Nunavik

Estimates of food insecurity at the community scale in Nunavik, using the Qanuippitaa dataset (collected in 2004), range between 9% and 52% (Figure 1) and are associated with high levels of uncertainty in the presence of low sample sizes. This descriptive statistical result identified the potential of the Qanuippitaa? How Are We? dataset to investigate the socio-cultural and economic determinants of

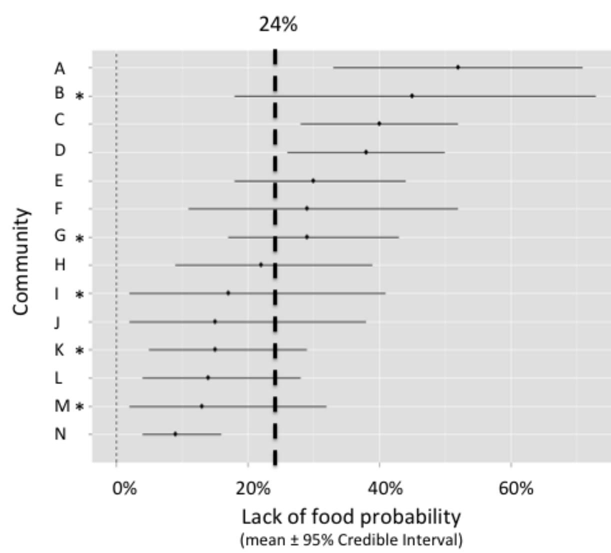

Figure 1. Distribution of lack of food probabilities at the community level in Nunavik from the 2004 Qanuippitaa? database. (*) indicates sample sizes smaller than 30 persons; the dashed line indicates the observed regional value (community names withheld).

household food insecurity at both regional and community levels. The analyses help fill a knowledge gap to support policy making as they illustrate the variability and capacity to discriminate between food insecurity at the community level within a regional database. This information can be used to support and prioritize actions to be taken in terms of interventions and more comprehensive studies on the topic in the future.

Project 3: Understanding Food Security Rates in Nunatsiavut

Significant diversity in community rates of food insecurity were found to exist in Nunatsiavut as well around the previously identified level of 45.6% food insecure reported in the Inuit Health Survey in 2007-08 (Rosol et al., 2012). Rates gathered under this research project ranged between 16% and 72% food insecure at the community scale. Initial results from descriptive analyses were shared with community leaders and local food security committees, as well as representatives of the Nunatsiavut Government and will be disseminated publicly this spring after which scientific publications will be submitted.

Project 4: Reconciling food security and wildlife protection needs

We held a workshop in May 2014 involving representation of harvester, wildlife Inuit health and nutrition interests. Through a series of plenary and participatory group activities, participants shared their expertise, to collectively develop a multidisciplinary vision of the local food system, and an understanding of the key dynamics relating environmental change, wildlife management/quota systems and food security and nutrition. This workshop was developed collaboratively with the Inuvialuit Settlement Corporation. This workshop was to validate our modeling results with the local hunters and trappers and public health professionals. We presented different scenarios and how they could be interpreted. Participants contributed inputs on how to better adapt the modeling strategies to better reflect local food choices.

Project 5: Developing a multidimensional instrument for a valid assessment of food security in the Canadian Inuit context (all regions)

We have furthered the work on the development of a new multidimensional tool for Inuit household food security assessment. Sensitivity, specificity and convergent validity tests have been carried out in 2014. A paper regarding the development of that tool is currently being reviewed by the IHS Steering Committee, and will be submitted as soon as we receive their approval (Philibert, A., Fillion, M. and Chan, H. M. (2014) "Development of a New Assessment Tool for Food Security for the Canadian Inuit Population", in revision").

Project 6: Documenting and evaluating food security interventions in the ISR: the Paulatuk community freezer case study

An initial inventory of food security initiatives has been conducted by Tiff-Annie Kenny in 2013 and 2014. Programs that target different aspects of food security were included in this inventory, according to the classification made in the CCA Report (2014): (1) Availability & Affordability of Healthy Foods; (2) Health & Education Programs; (3) Community Wellness & Intergenerational Knowledge Sharing; (4) Harvester Support & Sustainable Wildlife Management; (5) Poverty Reduction & Community Economic Development; (6) Infrastructure, Transportation & Local Food Production (CCA, 2014). This inventory was shared with the national Food Security Working Group led by ITK. During a visit to the ISR communities in the Fall 2014, this list was presented to the research collaborators and discussed. Additional initiatives and programs not previously identified were included to the list, mainly in the area of education. We are preparing a dissemination tool that present food security programs available in the ISR and how to access them.

Regarding the case study on the evaluation of community freezers, we have initiated a participatory process for evaluating the community freezer in Paulatuk. The goal, questions and methods for the evaluation have been determined in collaboration with Paulatuk's community freezer managers during a community visit in November 2014. The next steps of this evaluation have also been discussed, and it was suggested to do the data collection phase of the evaluation in March 2015. We are currently discussing the details of this phase with Paulatuk's freezer managers. Results of the community freezer evaluation are expected to be ready in May 2015. When this evaluation will be completed, the findings will be shared with IRC in order to see how to promote the sustainability of community freezers in the region.

Project 7: Developing a participatory food costing methodology to accompany food prices at the local level

We have developed a methodology to do participatory food costing in the ISR, based on the FoodArc methodology. The list of food items to be costed was developed according to the items of the Revised Northern Food Basket (RNFB) as well as a list of foods participants reported consuming commonly during the Inuit Health Survey. The adapted methodology was discussed with the regional dietitian for additional adjustments. With the collaboration of the regional dietitian, community research assistants were identified to conduct the participatory food-costing. During the ISR community visits of the Fall 2014, we have built capacity in 5 of the 6 communities by training a community research assistant to do the food costing. We have completed a first round of food costing in these communities and are working with the community research assistants and the ISR Food Security Working Group to improve the methodology to better reflect the local reality in the next round of costing and to develop effective strategies to share results with the communities involved.

DISCUSSION

Food insecurity is becoming recognized as one of the most important public health issues facing northern communities today. It is a valuable metric representing critical health issues within the household and as a result is gaining attention in all regions. Much of the work to date on the topic of food security and climate change in Inuit and other regions has reported, and as a result, depicted the levels of food insecurity to be homogenous at the regional scale. The results of the reanalysis of the Qanuippitaa? dataset In Nunavik and the generation of new data in Nunatsiavut shows that food insecurity is very much influenced by local factors such that levels can vary significantly between communities within the same region. As a result it is very important that the issue be investigated at the community specific scale and greater understanding of the determinants of food insecurity at this level be identified.

A variety of different assessment tools have been used to determine food insecurity rates in Canada and the Canadian North. It is only in Nunavik that it is currently possible to compare food security rates over time where the same tool has been used more than twice in the same region; results in this region are considerably lower than the other regions, yet qualitative reports from the region depict similar problems or challenges existing related to food access and availability.

Results obtained through the Inuit Health Survey in Nunavik (Rosol et al., 2012), where the highest rates of food insecurity in the developing world were reported, argue for the development of a new Inuit specific tool to assess this issue in various regions. One of the major shortcomings in the Inuit food security research to date is this lack of a specific, and yet simple instrument to accurately measure food security in Inuit communities. Our results in the development of a new tool based on the Inuit Health Survey show promise in accurately predicting food insecurity and showing the relationship between food security and key variables such as essential nutrient intake.

Our project is informing Inuit regional and community actions around food security. We have been moving the project from knowledge to action in this most recent year, engaging decision makers and community members on this issue across the North through scenario based discussions, regional workshops, community based household surveys and presentations and larger scale modeling activities and engagement with policy makers on the topic.

This study has brought together two multidisciplinary research teams and their networks working in different Inuit regions of the Canadian North. We have used complementary approaches to studying the relationships between environmental and other forms of change and food security status in Inuit homes. The project activities have enhanced the understanding of various aspects of the issue and have given rise to new initiatives and projects to pursue in many cases.

CONCLUSION

This project has worked to identify and help understand critical factors influencing food security in Inuit households throughout the North. It has generated new data, re-analysed existing datasets using new methods, and brought together previously unlinked data to increase our understanding of this important public health issue. It has explored the relationships between environmental factors, wildlife resources, socio-demographic data and household food security levels in different regions and how we measure and understand this phenomenon. It has engaged and supported community representatives, health and wildlife officials and practitioners, local, regional and Territorial decision makers in increasing their understanding and capacity to take action at appropriate scales on this topic. Finally, it has led to new initiatives that will continue to pursue a better understanding to improve actions to enhance access to safe, healthy, nutritious and culturally desired foods in Inuit communities throughout the Arctic.

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CLIMATE CHANGE AND FOOD SECURITY IN REGIONAL INUIT CENTRES

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ABSTRACT

Food insecurity is a chronic problem affecting many Inuit communities and is likely to predispose Inuit food systems to the negative effects of climate change. Using in-depth case studies, this project has identified and characterized the vulnerability and resilience of food systems in four regional Inuit centers to climate change (RICs) (Iqaluit, Arviat, Inuvik and Kuujjuak). Given the limited work on food systems in these communities, the work was structured around 2 phases. Phase 1 aimed to: i) document and describe the nature of food insecurity among at-risk populations in RICs, ii) characterize the environmental, biological and socio-economic determinants of food insecurity at various scales; iii) document coping strategies to manage food insecurity, and iv) examine the pathways through which climate change might affect food insecurity for at-risk peoples in RICs. Phase 2 has focused on policy linkages, and has sought to identify opportunities and priorities for adaptation intervention to enhance food security among high risk populations in the context of rapid current and future change, working closely with decision makers at multiple levels. In the final year of the project (2014/15) there has been a strong emphasis on knowledge translation in partner communities and at the regional level, including a multi-day workshop held in Iqaluit in June, along with the completion of student projects focusing on community identified research needs. The final year has also begun to develop new projects and collaboration to continue the work on completion through ArcticNet, including a targeted focus on food security among children in Iqaluit, the gendered dimensions of food insecurity in RICs in a changing climate, and examining what we can learn from Greenland for food programing in Nunavut (funded through the Government of Nunavut).

KEY MESSAGES

Knowledge translation

- A 1-day knowledge translation workshop was held in Iqaluit, June 2014, with the aim of presenting results to community, regional, and territorial decision makers and Inuit organizations, examining what the results mean for policy and programing across scales, and identifying next steps. The workshop was attended by >20 people and was followed with 5 days of individual visits to key stakeholders to discuss the work one-on-one.
- Two reporting events took place targeting decision makers in Kuujjuaq, including presentations to the Nunavik Regional Board of Health and Social Services (NRBHSS) (June 2014, February, 2014).
- NI Furgal assisted the NRBHSS expand their survey and review of food support programs in Nunavik.
- Project outreach was conducted in November 2014 to disseminate and discuss results from Anna Bunce's MA research on the gendered dimensions of food insecurity in Iqaluit.
- There was a strong team presence at the Arctic Change conference, with student work subsequently featured in Nunatsiaq News and on the CBC.
- A side event was organized at UNFCCC COP 20 meeting in Lima, Peru, profiling project findings to an international audience.

Research

- Our work in Iqaluit document that 33% of households with children were food insecure using modified USDA measure. No seasonality was detected in food insecurity.
- Climate change, in conjunction with socio-economic change, is impacting women's access to country food in Iqaluit, ability to spend time on the land, mental health, and connection to traditional activities such as berry picking and working with animal skins. Factors such as health, money, strong social networks, country food access and strong cultural identity have been identified as impacting the resilience of women in Iqaluit.

Networking

- Through the research conducted as part of project 3.7, the networks of collaboration created with northern decision makers, and policy-relevant research needs identified, new projects have been initiated (e.g. funded through Government of Nunavut).

OBJECTIVES

- Review findings from research conducted from 2011-2014 with community members and decision makers across scales, examining how the work can inform policy and programing, and identifying next steps.
- Organize knowledge translation workshop in Iqaluit and present work to an international audience.
- Present work at Arctic Change and organize a special session on vulnerability and resilience in northern communities.
- Identify opportunities for follow up work with partners, catalyze new partnerships, and develop projects to build upon the work conducted through ArcticNet.
- Continue targeted research on key food security related topics identified by knowledge users (e.g.

gender and food security in a changing climate, children and food security).

INTRODUCTION

Since the inception of this ArcticNet project, food security has emerged as a major political issue in the North, with rates of food insecurity among Canadian Inuit significantly greater than the Canadian average. Research has played a major role in characterizing the magnitude of the food security challenge, identifying factors which contribute to the problem. A lot of this work has focused on smaller, more remote communities or has examined prevalence of food insecurity at a regional scale without differentiating by community (e.g. studies conducted as part of the Inuit Health Survey). This work has significantly contributed to our understanding on food insecurity, and has been used by Inuit organizations to draw attention to the challenge and need for a strong and coordinated policy response. Lacking in this research, however, has been a focus on the larger regional centers of the North, including the territorial capital cities and regional centers (e.g. Inuvik, Rankin Inlet). These rapidly growing settlements are home to a significant number of residents of northern Canada, and differ in social-economic-demographic structure from smaller communities where research has primarily been conducted. This project sought to address this research gap, characterizing the challenge of food insecurity in regional centers, identifying the role of various social, economic, and cultural factors affecting food systems, and examining how climate change may impact already stressed food systems.

To achieve its objectives, the project catalyzed a team of food security researchers, students, community members, and policy makers from across the North to examine the experience and determinants of food insecurity. The project had a specific focus on 'high risk' groups and how underlying socio-economic-cultural factors affect resilience and vulnerability to climate change. The project leveraged significant co-funding (e.g. $1.2M CIHR IK-ADAPT project, $2.5M IDRC IHACC project), and networked with other ArcticNet food security projects focusing on smaller communities (e.g. project 4.1). The work conducted was particularly timely, and coincided with the Government of Nunavut developing a food security strategy. The project directly informed this strategy, with former MA student Sara Statham (who was trained through this project) recruited to be the food security coordinator for the GN and who had a leadership role in developing the strategy.

Over its four years, the project has made major contributions to understanding of food systems in regional centers. Headline results include:

- Food insecurity in larger regional centres is less pronounced than in the smaller communities, but still remains high compared to southern Canada, and is a chronic problem among a subsection of community members. Community food programs are important for meeting the needs of the highly food insecure, but provide only a stop-gap measure and indicate the need for broader food system enhancement.
- Determinants of food insecurity in larger regional centres primarily reflect socio-economic factors, with climate change less pronounced as a stressor than smaller communities. This derives from the stronger wage economies and reduced dependence on traditional foods.
- Seasonality does not appear to have a major influence on food insecurity, at least in surveys conducted in Iqaluit. While this requires further analysis, we hypothesize that a strong wage economy provides some buffering to variations in access and availability of traditional foods.
- Determinants of food insecurity ultimately act at the national scale, with colonial legacy important to consider. Interventions to enhance the resilience of the food system in-light of multiple stresses need to focus on multiple scales, not just the local.

- There is limited research and policy discussion on how to adapt to the health effects of climate change, including to potential food security implications. Adaptation needs to be mainstreamed into ongoing policy planning to be effective.

In the final year of the project (2014-15), a major focus has been on translating the knowledge developed to knowledge users at various scales, identifying next steps, and catalyzing new research programs that build upon the research and collaboration established. We have also sought to research specific topics identified by our partners. This progress report focuses on these activities conducted during the final year.

ACTIVITIES

1. Knowledge Translation (KT)

An overarching goal of the project was to directly contribute to decision-making processes around food security in a changing climate. Recognizing that moving knowledge to action goes beyond just raising awareness or providing information, the project focused on the co-development of understanding, sought to break down barriers between producers and users of knowledge, engaged knowledge users from across scales, and worked together to create understanding and shared knowledge. This has been ongoing throughout the project, with specific KT activities organized on an annual basis and including community information nights, feasts, targeted policy briefs, one-on-one meetings with decision makers, and presentations. These are described in previous annual reports, and primarily focused on Arviat and Inuvik. In recognition of this, project publications were profiled in a UN report on best practices for engaging traditional knowledge in adaptation research.

1.1 Iqaluit workshop

In 2014/15 one of the main KT activities involved organizing a knowledge translation workshop in Iqaluit. Decision makers in various levels of government, Inuit organizations, and civil society were invited along with community members and public health practitioners. Over 20 people attended, including representatives from NTI, the GN, Iqaluit public health, the city of Iqaluit, AANDC, and PHAC. The workshop began with faculty (n=2) and students (n=5) giving presentations on their research projects, along with a summary overview of the findings of the recently released IPCC AR5 and what is says for the North. Emphasis was then placed on discussing the findings with those present, specifically about how the results might be used in decision making, how the results should be communicated more broadly, and who we should connect with who was not present at the workshop. We finished by identifying future research needs, and how research can inform future policy and programing in the territory. While the focus of the workshop was primarily on the Iqaluit work, we also presented relevant findings from other communities. In addition, we met individuals not at the workshop one-on-one to discuss the findings from the work, along with those who wanted additional info (e.g. NTI, Qaujigiartiit Health Research Centre).

1.2 Further Iqaluit dissemination

Anna Bunce's MA thesis is examining the gendered nature of vulnerability and resilience to the food security implications of climate change in Iqaluit. She conducted her fieldwork primarily after the June workshop, and returned to the community in November to disseminate and discuss her findings. This including meeting representatives of the GN Department of Health, NRI, Qulliit Nunavut Status of Women Council, NTI, Department of Environment, and a variety of community members. She also met with Pauktuutit in Ottawa on December 12th.

1.3 Kuujjuaq dissemination

Two reporting events took place targeting decision makers in Kuujjuaq, including presentations to the Nunavik Regional Board of Health and Social Services (June 2014, February, 2014). At this time, project results were presented and implications of the findings were discussed.

1.4 Broad level KT

In the final year we have also targeted presenting our work at academic conferences. The project had a strong presence at Arctic Change, including:

- 2 student presentations (Anna Bunce: "Inuit women and climate change"; Knut Kitching: "Tuktu and climate change: Inuit harvesting on south Baffin"). Anna Bunce's presentation formed the basis of an article in Nunatsiaq News and CBC North news feature.
- The PI organized a special session (Ford & Pearce: "Community Adaptation and Vulnerability in Arctic Regions").
- 1 poster (Ford: "Inuit Traditional Knowledge for Adapting to the Health Effects of Climate Change").
- 1 partner presentation (Statham: "The Nunavut Food Security Coalition's Value Toward and Need for Food Security Research").

We also presented the work in a side event at the UNFCCC COP20 meeting in Lima, attended by >100 people, and to an invited presentation given at Griffith University, Australia, in May. In April, the PI, was invited to brief the UN in Bonn on the role of traditional knowledge in climate change adaptation, drawing on work conducted during this project.

2. Research

Targeted follow-up research projects responding to research needs identified in phase 1 of the project were initiated in 2013, and entered their final phase in 2014/15. Firstly, Catherine Huet has used data collected in a food security survey applied to Iqaluit in 2013&2013 (n=431) to focus specifically on prevalence of food insecurity and risk factors among Inuit households with children. This advances previous analyses which have looked at the population of Iqaluit as a whole and responds directly to community interest. Secondly, MA student Anna Bunce is examining how Inuit women in Iqaluit are experiencing and adapting to the food security implications of climate change. She conducted fieldwork in Iqaluit in summer 2014, with follow up work in November, including 42 interviews, 2 focus groups, and a photovoice exercise. This focus explicitly builds upon previous work in Iqaluit which identified concern over women's access to country food in-light of multiple stresses. Thirdly, MA student Knut Kitching is finishing up his thesis developing a baseline understanding of the sustainability of caribou harvesting in the Iqaluit region. Finally, the project acted as a foundation for a larger review of food support programs in all communities by the Nunavik Regional Board of Health and Social Services (NRBHSS) using the same data collection and analytical template we developed. This information is being provided to the newly created Nunavik Food Security Working group in discussions for the development of a regional food strategy. NI Furgal also assisted the NRBHSS expand their survey and review of food support programs in Nunavik.

3. Follow up work

The community-based participatory research nature of the project has leveraged significant support at a community level, among Inuit organizations, civil society, and at various levels of government. Food security is a major concern across the board, and need for additional research has been identified during the course of the project. In one recently developed project - developed with partners here - we have received funds from the Government of Nunavut's Dept. of Health to examine food programing in Greenland, examining if the commercialization of traditional foods has enhanced food security. Our partners in Nunavut have expressed significant interest in learning from the Greenlandic experience and the work is designed to inform emerging debates on the role of traditional food markets in northern Canada. In another program proposal, the PI and NIs are applying for funds from CIHR to expand develop an explicit climate change adaptation focus in food security studies.

RESULTS

Given the explicit and overarching focus in the last year of the project on KT, a key result from the work has been enhancing knowledge and understanding on food security in case study communities and regions, particularly the situation of high risk groups. We have not yet formally evaluated the success of these activities in terms of their influence on policy and programing, noting the work was well received among decision makers we have met with. Examples here of follow up work catalyzed by results dissemination activities include the GN commissioning the PI to examine what we can learn from Greenland for food programing in Nunavut; NTI identifying specific follow-up areas for further analysis (examining Inuit-specific food security data in Iqaluit, focus on households with children); the Nunavut Food Security Coalition identifying the importance of continuing the work we are doing on ArcticNet phase 3 completion; and NI Furgal assisting the NRBHSS to expand their survey and review of food support programs in Nunavik.

1. Climate change, gender, and food security in Iqaluit

Using a gender analysis and vulnerability approach, Anna Bunce's thesis is examining how Inuit women in Iqaluit, Nunavut are experiencing and adapting to climate change. In doing so, the work is specifically characterizing how women are experiencing and interacting with climate change, identifying the factors that positively or negatively impact their adaptive capacity, highlighting adaptations and coping strategies that are being developed and discussing participant identified adaptation priorities. Preliminary results document that climate change, in conjunction with socio-economic change, is impacting women's access to country food, ability to spend time on the land, mental health, and connection to traditional activities such as berry picking and working with animal skins. Factors such as health, money, strong social networks, country food access and strong cultural identity have been identified as impacting the adaptive capacity of women in Iqaluit. Specifically, the work has a strong focus on berry picking, which is becoming less accessible for women due to climatic change and infrastructural growth. As the climate changes there have been a series of "bad berry years". During these times berries are less readily available and when they are available they are smaller and seedier. Since berry picking is an activity requiring minimal financial investment or time commitment, this traditional activity has been something women can do whether they are busy with children or busy working. Many women stated feeling a connection to their Inuit identity while berry picking and as this activity becomes more difficult to access this becomes another way women are being distanced from traditional harvesting activities.

Peer reviewed article in prep

- Bunce, A., and Ford, J. The treatment of gender in climate change impacts, adaptation, and vulnerability research. To be submitted to Global Env Change.

Presentations

- Bunce, A. (2014, December). Inuit women and climate change: Perspectives and experiences regarding climate change and adaptation in Iqaluit, Nunavut. Presented at Arctic Change 2014, Ottawa.

- Bunce, A., Petrasek-MacDonald, J., Mallait, M. & Labbe, J. (2014, October). Inuit Women and Environmental Change:Examining experiences and adaptations in Iqaluit, Nunavut. Presented to Geographical Perspectives on World Environmental Issues class at McGill University, Montreal, QC.
- Bunce, A., Labbe, J., & Austin, S. (2015, January). Exploring Vulnerability and Adaptation. Presented to Human Dimensions of Climate Change class at McGill University. Montreal, QC.

Media outreach

- Rogers, S. (2014). The climate is changing, and so are Arctic berries. Nunatsiaq News Online. Nunavut. Retrieved from http://www.nunatsiaqonline.ca/stories/article/65674the_climate_is_changing_and_so_are_arctic_berries/.
- CBC Northbeat (2014). How climate change affects Inuit women. (2014, November 26). Northbeat. Iqaluit, Nunavut. Retrieved from http://www.cbc.ca/player/News/Canada/North/ID/2618485830/.

2. Food insecurity in households with children in Iqaluit

Using data collected from a randomized food security survey conducted in Iqaluit in 2012 & 2013, team member Catherine Huet has estimated the prevalence of household food insecurity and associated food habits in households with children during two seasons in Iqaluit (sample size = 431). Results analysis is ongoing with emerging results indicating: food insecurity was identified in 33% of households with children but prevalence was not significantly different between seasons ($P > 0.05$); ethnicity, education, employment status and household expenses were significantly different among food security statuses in both seasons ($P < 0.001$); and in both seasons, fruit and vegetables consumption, as well as cooked and frozen preparations of meat and/or fish were significantly different between the food security statuses ($P < 0.05$).

Peer reviewed article in prep

- Huet, C., Ford, J. et al. Seasonal food insecurity relates to food habits in households with children in an Inuit community. To be submitted to Int. Jrn of Circumpolar Health.

Presentation

- Ford, J. et al. Food insecurity in Iqaluit. Presentation at results sharing workshop, Iqaluit, June 16th 2014.

3. Caribou and climate change on south Baffin

MA student Knut Kitching is finishing up his thesis developing a baseline understanding of the sustainability of caribou harvesting in the Iqaluit region in the context of changing access, climate-driven caribou population changes, and a number of management frameworks and institutions. Specifically the work has a focus on how hunters are adapting their behaviors to changing access to harvest areas and variations in caribou populations.

Presentations

- Kitching, K., and Ford, J. Tuktu and climate change: Inuit harvesting on southern Baffin Island. Oral presentation, Arctic Change, Ottawa, December 2014.
- Kitching, K., and Ford, J.Tuktu and Climate Change: Inuit Harvesting on Southern Baffin Island”, CIHR National Gathering of Graduate Students, Simon Fraser University July 2014.

DISCUSSION

Over its four years, the project has made major contributions to understanding the food security challenge in regional centers. Headline results include:

- Food insecurity in larger regional centres is less pronounced than in the smaller communities, but still remains high compared to southern Canada, and is a chronic problem among a subsection of community members.
- For the food security survey we conducted in Iqaluit, Inuit households were significantly more likely to be food insecure than non-Inuit households.
- Across our partner communities, community food programs are important for meeting the needs of the highly food insecure, but provide only a stop-gap measure and indicate the need for broader food system enhancement.
- Determinants of food insecurity in larger regional centres primarily reflect socio-economic factors, with climate change less pronounced as a stressor than smaller communities. This derives from the stronger wage economies and reduced dependence on traditional foods. Yet examples of population declines of key wildlife resources such as caribou on south Baffin (which may have some climate link), indicate significant potential future vulnerabilities associated with climate change. Similarly, challenges facing berry pickers in light of a changing climate are impacting access to a highly valued seasonal food source, negatively affecting well-being.
- Households use a variety of coping mechanisms to manage variability in access, availability, and quality of traditional foods. Yet not all households have the resources (financial, social, knowledge) to cope, with climate change exacerbating existing inequalities.
- Seasonality does not appear to have a major influence on food insecurity, at least in surveys conducted in Iqaluit. While this requires further analysis, we hypothesize that a strong wage economy provides some buffering to variations in access and availability of traditional foods.
- Determinants of food insecurity ultimately act at the national scale, with colonial legacy important to consider. Interventions to enhance the resilience of the food system in-light of multiple stresses need to focus on multiple scales, not just the local.
- There is limited research and policy discussion on how to adapt to the health effects of climate change, including to potential food security implications. Adaptation needs to be mainstreamed into ongoing policy planning to be effective.

Our focus on knowledge translation in 2014/15 has presented and discussed these results with decision makers across various scales. Herein, the results fill an important gap at various levels. For example, before the project was initiated, those involved in community food programing had limited understanding of who was using their programs and why, how this was changing over time, and potential future trends in usership; there was limited understanding on the prevalence and risk factors for food insecurity in our partner communities and how they compare to regional trends; the gendered dimensions of food insecurity were little understood beyond some studies noting high rates of food insecurity among females; and climate change as a potential risk factor for food insecurity largely unexamined in the larger regional centers. The work conducted here helps address these questions yet it is also clear that the project represents a staging point for a more in-depth examination of food security challenges in regional centers, with direction for future research including: more explicitly identifying and evaluating specific policies, programs, and initiatives at community to territorial levels that could be used to strengthen northern food systems in-light of multiple stresses; examining what we can learn from other jurisdictions for food programing (e.g. Greenland); examining in greater depth links between climate change and food insecurity, with an explicit future focus and examining potential for adaptation to be integrated into decision making activities. These form the basis of planned future work, and some cases have been initiated through secured external funding.

CONCLUSION

Since 2011 we have worked closely with researchers, students, community members, and decision makers from across the North to examine the experience and determinants of food insecurity in Regional Inuit Centres (RICs). The project has developed baseline understanding of the challenges posed by a rapidly changing climate to food security in RICs, alongside characterizing the magnitude of the problem currently posed by food insecurity, particularly among high risk groups. 2014/15 focused primarily on knowledge translation, discussing results with communities and decision makers and identifying next steps. While 2015 represents the formal completion of the project through the ArcticNet funding cycle, the work will continue through initiatives funded through CIHR and others. In particular, a strong food security network has been created through this project which will continue to work towards identifying how we can work together to enhance the resiliency of northern food systems to multiple stresses.

ACKNOWLEDGEMENTS

The team are grateful to the community members in Arviat, Kuujjuaq, Iqaluit, and Inuvik who participated in this study. The project also collaborated closely with numerous organizations and governments at various levels. There are too many individuals to name personally, and we'd like to thank all those who helped with the study. The project would also not have been possible without support from SSHRC, CIHR, NSERC, IDRC, Government of Nunavut, and the Public Health Agency of Canada, who all made cash contributions to the work.

PUBLICATIONS

Beaumier, M. Ford, J. et al, 2015, What role does climate change play in affecting the food security of Inuit women in the Canadian North: A case study from Arviat, Nunavut, Polar Record, In press.

Ford, J., Cunsolo-Willox, A., Chatwood, S., Furgal, C., Harper, S., Mauro, I., and Pearce, T., 2014, Adapting to the effects of climate change on Inuit health., American Journal of Public Health 104(S3), 1-9.

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INUIT KNOWLEDGE AND GEOSPATIAL ONTOLOGIES IN NUNATSIAVUT

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ABSTRACT

There is an urgent need to document and share the extensive and valuable knowledge held by Inuit Elders and other Inuit experts with local Arctic decision makers, younger generations, and with members of the scientific community to better to understand pressures on and changes in these systems. In the context of ongoing and impending new development, there is a need to capture and communicate changes in Inuit Knowledge (IK) and use of the land. Geographic Information Systems (GIS) and other spatial data organization and representation technologies have been used for a variety of applications for, with, and by Indigenous groups in recent decades (e.g. land use planning, natural resource management, land claims negotiations, documentation and transmission of IK to younger generations). Processes such as Participatory GIS (PGIS) and the development of geospatial ontologies methods of capturing and representing Indigenous conceptualizations of spatial phenomenon can be empowering and create useful tools to illustrate and communicate IK and concepts of the environments. When focused on current important cases, such as Inuit Knowledge of key species undergoing dramatic change (e.g. caribou), or land use mapping of currently changing, or threatened areas (e.g. lands likely to be impacted by industrial development) efforts of this nature have the potential to create tools that can support local decisions about the environment and its resources, in ways that better reflect local understandings and cultures. This project is conducting a geospatial ontology exercise with expert knowledge holders in the Nunatsiavut Settlement Area. The long term goal is the development of a geospatial ontology application and interface that complements existing GIS for use in land use planning, environment and development decision-making as well as Nunatsiavummiut Knowledge (NK) representation and transmission to a variety of audiences. This project is a partnership between the Nunatsiavut Government (NG), local knowledge holders and University-based researchers. The short term results are expected to provide representations of NK on key issues in support of decision making needs around land and development in the region while the longer term results are expected to provide evidence for a different and potentially more culturally-specific way of accessing and using Inuit Knowledge in decisions about land and landscape in Nunatsiavut and other Inuit regions.

KEY MESSAGES

- This project has been developing a Nunatsiavummiut Knowledge (NK)-based ontology and interactive computer interface to access documented NK of the land and environment.
- Based on NK and conceptualizations of the land around one case community (Nain), and with a particular thematic emphasis on land use and caribou, this ontology can provide support to decision makers through facilitating access to documented NK in the region and displaying it in mapped interface.
- Interviews and focus groups with knowledge holders and land experts in the region have documented key Inuit Knowledge needed for regional decisions on land use (in the Voisey's Bay and Strange Lake areas) and caribou management (Torngat Mountains herd), as two examples to be used in the development and illustration of the prototype system.
- A prototype ontology has been developed and these two components of the project are being linked to show new representation formats for IK in the region to support environment related decision processes.

OBJECTIVES

- Complete analysis and reporting for two NK documentation cases in NUnatsiavut (Torngat Mountains Caribou Herd NK and land use south of Nain in the Voisey's Bay and Strange Lake areas).
- Complete development of prototype Nunatsiavut ontology of aspects of the environment and land for the construction of the unique NK based decision support system that includes geographic representation of this information.
- Interact with key regional decision makers to present, review and adapt the prototype interface.
- Communicate findings on Inuit geospatial conceptualizations of land and the environment via presentations to decision makers, the research community via conference presentations and publications.

INTRODUCTION

The context and rationale for this ongoing project has not changed or evolved since its inception. As such, this Introduction remains largely the same for this final year of the project as presented in previous reports.

Geographic Information Systems (GIS) and other spatial data organization and representation technologies have been used for a variety of applications for, with, and by Indigenous groups in recent decades (e.g. land use planning, natural resource management, land claims negotiations, documentation and transmission of Traditional Knowledge to younger generations) (Bocco et al. 2001, Duerden and Kuhn 1996; Laituri 2002; Tobias 2000). It is argued that through processes such as Participatory GIS (PGIS) and geospatial ontology research methods of capturing and representing Indigenous conceptualizations of spatial phenomenon, such initiatives can be empowering and create useful tools to illustrate and communicate Indigenous Knowledge (IK) and concepts of the environments which local people understand so well. Additionally, these efforts have the potential to create tools with which to make local decisions about the environment and resources which better reflect local understandings and cultures (Wellen and Seiber, 2012).

Conceptual ontology research in geography attempts to understand how people think about and organize geographic phenomenon (Agrawal 2005; Smith and Mark 1998). It is more than simply GIS representation of geographical data or human use of the landscape. A prime goal of geographic ontologies is to make explicit the geographical categories embodied in a geographic information database such as a GIS system. Previous research in this area with Indigenous groups has been conducted predominantly in more southern regions of the globe. It illustrates how people from different cultural and language groups use different categories to make sense of the geographic world, and that these different sets of categories do not map onto each other in a straightforward manner. Most conceptual ontology research has focused on Aborigine groups in northwestern Australia and the Navajo in the United States (Mark and Turk 2003; Stea 2007; Mark et al., 2007) with more recent work being conducted among Cree in James Bay (Wellen, 2008, Wellen and Sieber, 2012) and by Fletcher and others in Labrador with the Ashkui (Innu Cultural Landscape Unit) project (as in Furgal et al., 2006). Associated work in the Inuit context is represented in work by Laidler (2006) in her Inuit representations of sea ice formation and dynamics and linguistically in the Inuktitut terminology workshop held by Nunavut Tungavvik Inc in 2005 to which team member (C. Furgal) was an advisor and participant.

In the context of environmental, economic and political change, a fundamental question at the centre of the Nunatsiavut Government dialogue is the issue of land use management and decision-making processes. It is vital that Inuit land use and, more importantly, Inuit Knowledge and values associated with land are at the core of this new way forward. This project, a partnership between the Nunatsiavut Government (NG), Nunatsiavummiut Knowledge (NK) holders and University-based researchers is conducting pilot Inuit geospatial ontology research. The NG is ideally positioned to take immediate advantage of the outcomes of the study and incorporate them into policy and legislation. The Nunatsiavut Government is currently at an early stage in its governance structure and even though this is a pilot study, it has been designed so that the outcomes are directly relevant to the priorities of the young government. The Nunatsiavut Government will consider the outcomes to help guide land use management processes as well as inform environmental assessment and protection regulation deliberations in the context of climate change and development in the region. This project directly supports and informs future actions under the newly established Nunatsiavut Environmental Protection Legislation and Environmental Assessment Act of the Nunatsiavut Government.

It is hoped that the outcomes of this work will also provide Inuit regions across the Arctic with a template and process to better incorporate and represent IK-based conceptualizations and classifications of land and environmental phenomena and cultural values into land management and development decisions.

The final year of funded work under this project has focused on bringing the NK documentation initiatives (land use and caribou) to a close and reporting and communicating those results. Additionally, significant time was focused on completing the development of the prototype interface for displaying this knowledge in a geospatial interactive environment and refining that interface through feedback from regional decision makers. For descriptions of earlier stages in the process of the project please refer to previous year's reports. What is presented here is an update on activities and outcomes of the work conducted in 2014-15.

ACTIVITIES

1. Collection of IK pertaining to caribou and Inuit land use

All data collection was completed on the Inuit Knowledge, culture and values of the Torngat Mountains Caribou herd from Nain and Kangiqsualujjuaq. Verification of transcripts was conducted with participants and validation presentations were made in each of the communities to permit participants to review and approve the interpretation and presentation of the data being made. A final report was prepared for this study (in English and Inuttitut - Nunatsiavut and Nunavik dialects) (Wilson et al., 2014), including production of all maps. The report has been circulated to all project partners for distribution to participants. A copy of the report was submitted for consideration in the preparation of the COSEWIC report on this species.

All revisions to mapped data on Inuit land use and knowledge of the region south of Nain stretching from the Labrador coast inland to the Quebec-Labrador border were completed. Significant revisions were made to the draft report and maps. The final report is being prepared for spring 2015 release (Furgal et al., 2015). The database was provided to Pulsifer for consideration in the presentation of data in the geospatial ontology interface tool.

A review of all existing land use data in this region was conducted and an initial spatial analysis of the extent of recorded land use in the area around Voisey's Bay was done. Existing qualitative data on land use in the area was gathered and is being analysed similarly for indications of changes in land use over time in this area in relation to development and environmental change.

2. Development of Inuit Ontology and Computer Platform Interface

Significant data and software development activity took place during 2014-15. Led by Pulsifer, the preliminary ontology and concept model established through review of the seminal land use document entitle *Our Footprints are Everywhere* (Brice-Bennett 1977, Pulsifer et al. 2013) was significantly enhanced to include recent land use data collected through what was originally the Labrador Inuit Association Resource Harvesting Study Winter of 2004-2005. Data through 2013 was used to establish a knowledge model (ontology) stored as a semantic web compatible Resource Description Framework-Web Ontology Language (RDF-OWL) database. This knowledge model was then linked to actual instances of GIS data representing a variety of different land use and subsistence concepts including wildlife observations and harvesting locations and places of significant importance (e.g. Voisey's Bay mine). The creation of this database highlighted the complex and nuanced relationships between Nunatsiavimmiut, institutional, and academic knowledge of the environment and land use practices. These bodies of knowledge include spatiotemporal concepts related to the change in the landscape over time, for example, and other more abstract concepts such as the value placed on various forms of economic development. It became clear that to represent these concepts and associated data without the use of advanced technology would require the development of a tool appropriate for visualizing concepts, data and relationships.

In keeping with the project objective of making Inuit Knowledge concepts and related data available to land use planners and others who may not have advanced expertise in the use of modeling and analysis tools (e.g. GIS), a relatively simple, web-based software tool was developed (see Results). Using prototypes developed in earlier phases of the project (Pulsifer et al. 2012, Pulsifer et al. 2013), custom source code was written to link together a number of existing open source software packages including OpenLayers (http://openlayers.org/), D3 (http://d3js.org/), and RDF (https://github.com/jimmccusker/rdfviewer). The new package, also released available under an open source license via a source code repository (SVN, available upon request), integrates concept visualization, temporal filtering, and geographic mapping capabilities. While all of these capabilities existed independently or in advanced desktop software, providing these functions together in an integrated web-based tool is an innovative way to provide land use managers, community members and with ready access to representations of knowledge and data.

The software was designed with interoperability in mind. The knowledge model and geographic data are stored in international standard formats that can be made available via an Internet accessible web service. Because it is using RDF/OWL as a foundation format, data are compatible the linked data and semantic web approach to interoperability.

A presentation of the initial prototype was provided for project co-lead and Nunatsiavut Government representative, T. Sheldon, after which further adaptation of the interface tool took place.

Finally, the tool, as a potential tool for use in the translation and presentation of environmental and human data (in this case originating from Inuit Knowledge and land use observations) for decision making and policy support was presented at the Arctic Change 2014 Conference in a special session organized on the topic of the science – policy interface.

One manuscript is currently in draft to communicate some of the findings on the work to develop an ontology and interface and is planned for submission in late spring 2015.

RESULTS

1. Collection of IK pertaining to caribou and Inuit land use

Caribou

The Torngat Mountains Caribou Herd (TMCH), inhabiting the northern tip of the Québec-Labrador Peninsula, is not well documented in regard to science or Inuit Knowledge. Limited information on this herd suggests a recent population decrease. Given the importance of caribou for Inuit, precipitous declines in the neighbouring George River Herd, and the upcoming Committee on the Status of Endangered Wildlife in Canada assessment, increasing our understanding of these animals through documentation of IK is critical. This sub-project drew together Inuit from Nunatsiavut and Nunavik and government agencies, from regional to federal levels and across provincial borders. Thirty-three semi-directed interviews were conducted, including participant mapping, with hunters and Elders in Nunavik and Nunatsiavut, representing over seven decades of IK. Thematic content analysis was performed on interview narratives, highlighting IK on this species including new information about topics like the changing role of predators and herd behaviour. Digitized spatial data visualized the long-standing Inuit-caribou relationship in the area, while augmenting the limited existing geographic information. Considerable depth and breadth of IK in Nunatsiavut and Nunavik regarding caribou and their ecology was evident (e.g. Figure 1), representing contributions to the overall understanding of TMCH ecology, particularly as it pertains to assessment and future Species At Risk Act designation for this herd or future Inuit wildlife stewardship decisions.

Land Use

The documentation of Inuit Knowledge and land use in the area south of Nain reaching from the sea ice edge to the Quebec – Labrador boarder highlights the ongoing nature of the connection between Nunatsiavummiut and the environment. Interviews, focus groups and participant mapping was used to document knowledge from participants of Nain, Makkovik and Hopedale. It represents knowledge, perspectives and observations on the environment since the release of From Sina to *Sikujâluk* in 1997 (Williamson). The data show that Nunatsiavummiut hold a vast wealth of knowledge of the land and sea in this region that builds on generations of close relationship through travel, hunting, fishing, gathering and occupation. In regards to the development of the Inuit ontology and visual interface prototype the data gathered here highlights the expansive use and connection to a vast territory by Inuit in the area. Further, the knowledge shared in this sub-projects conveyed the meaning of many land and sea features with which Inuit interact in the area on a regular basis. For example:

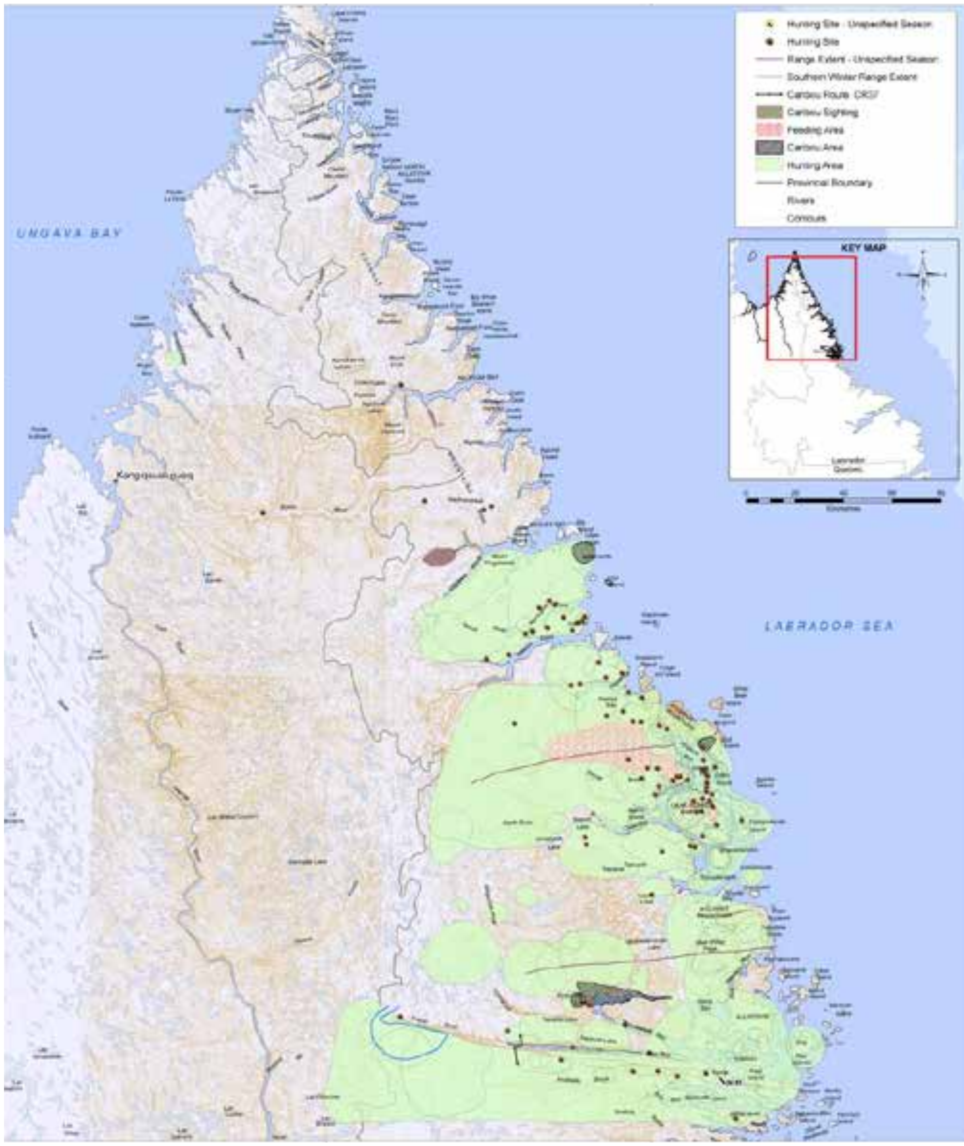

Figure 1. Winter (December to February) caribou-related information from Nunatsiavut participants.

- The large number of cabins and common camping sites throughout the study area that are used in many if not all seasons by residents of the three participant communities is indicative of a continued, significant use of this region.
- The substantial footprint of activity as presented on the maps show multi-seasonal use of the marine environment in the east, and travel and hunting activity nearly to the western limit of the study area by Inuit during the last 15 years.
- The study area represents a rich and diverse region in terms of wildlife biodiversity, which is critically important for Inuit in the region today. The use of the region for hunting caribou and fishing for Arctic char stand out among all other species. There are a number of key locations or sites within the study area where many

activities important to the residents of the three participating communities commonly take place in one or many seasons (e.g., Ikadlivik Brook, Kamarsuk, etc.).

- Further, the importance of a stable inshore marine environment inclusive of sea ice regimes upon which Inuit rely for winter travel, the richness of the coastal island habitats for migratory bird nesting, and the sensitivity and critical nature of many river valley ecosystems heading inland to the west from Voisey's Bay and Anaktalâk Bay cannot be understated. These are all critical features of an important and productive landscape for Inuit.

It was possible to gather and access datasets representing Inuit land use and connection to place in this area from pre 1980 (*Our Footprints Are Everywhere*), the time since then and prior to the development of Voisey's Bay (*From Sina to Sikujaluk*) and since the opening and operation of the mine until two years ago (current sub-project). The spatial analysis of existing datasets describing Inuit land use in and around a key development site in the region (Voisey's Bay) has not identified any significant changes in land use or connections to place as of yet, however this analysis is ongoing. Similarly, we have gathered and brought together all qualitative datasets describing land use and connection to place in this area over time as well and a qualitative analysis of this data is underway to determine changes over time in association with development and/or environmental change.

2. Development of Inuit Ontology and Computer Platform Interface

Software Application Development

During this reporting period the project team developed a software package that provides an interface that combines conceptual, spatial and geographic representations. A prototype of the application can be accessed at: http://heicresearch.com/nunatsiavut_onto/webapp/index.html. The application supports concept mapping, geographic mapping (Figure 2) and temporal filtering (Figure 3).

Initial indications are that developing an interface that combines conceptual, spatial and geographic representations provides an extremely valuable foundational tool for land use management process in Nunatsiavut. This preliminary conclusion is based on demonstration of the tool to key land use management staff at the Nunatsiavut Government (NG). Feeback suggests that integrated temporal modeling provides better representation of the living, dynamic nature of Nunatsiavut Knowledge and land use practices. Additionally, interoperable design supports connection to many additional data resources held by the NG and other agencies.

DISCUSSION

The importance of mapping land use and land 'formations' is a common discussion in the environmental management and land use planning literature. The use of GIS and participatory GIS (PGIS) generated databases are identified as the preferred tool of use by Indigenous communities, industry and governments in making land use decisions. The map biography method complements GIS by integrating oral history, perceptions of history and geographical and environmental knowledge (Usher, 2003). As a result, mapping complemented by the narratives of Indigenous community members and their observations and knowledge of the landscape are critical sources of data upon which to make more sustainable land use decisions in many regions of the North (Kendrick and Manseau, 2008). The ArcticNet supported project presented here has worked to bring these two elements together in one Inuit region of the Canadian North and present that information in a more appropriate and accessible form than has previously been done. 'Appropriate' in this case, refers to the development and organization of data in an

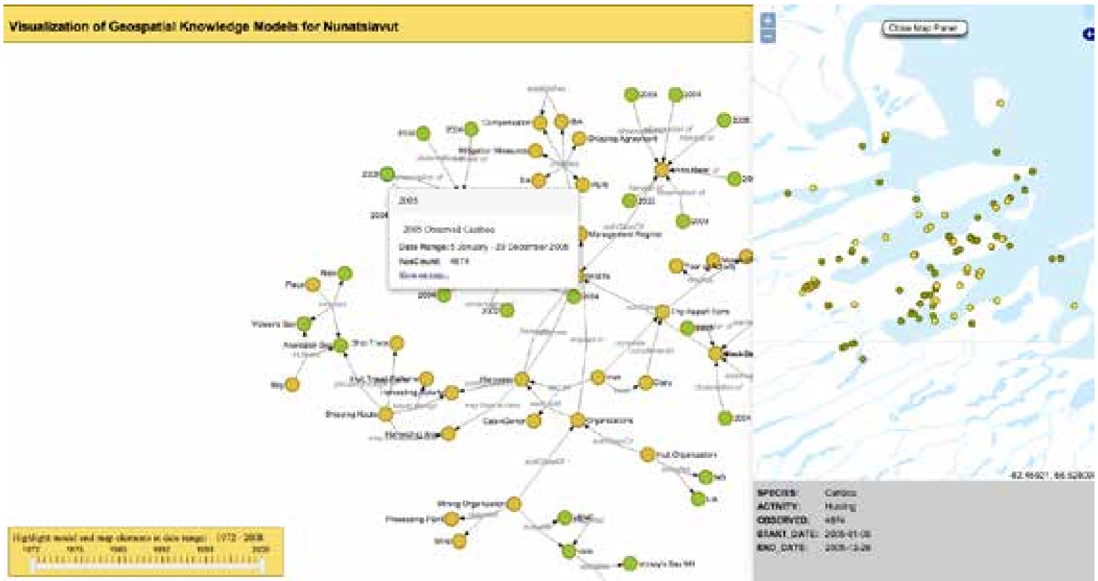

Figure 2. Where data exists, instances of data related to a geographic concepts can be mapped.

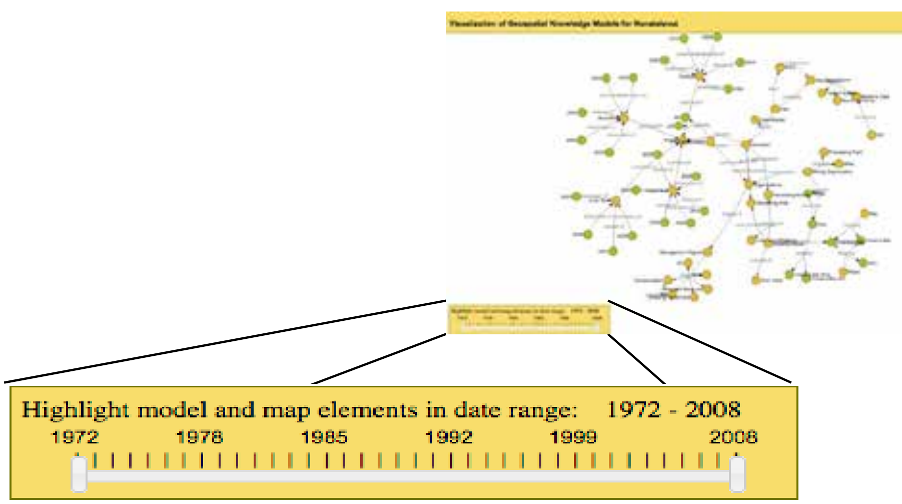

Figure 3. A timeline slider bar can be used to filter concepts and data on temporal attributes.

Inuit generated ontology, while 'accessible' refers to the prototype digital interface developed under this project.

Development of the current iteration of the knowledge model and the software application significantly increased our knowledge of how to move forward in making knowledge and data more accessible across knowledge domains. We established that mapping and knowledge modeling is complex and time consuming but that it resonates with knowledge holders. In addition to knowledge gained while creating the knowledge model and software, and producing tangible artifacts, much was learned through the process of developing these tools. We confirmed that an iterative approach that involved all project stakeholders at appropriate points in time was very effective in identifying necessary building blocks, appropriate representation, and interaction models. It is also clear that designing for interoperability is more costly in the short-term, however using this approach meets a critical need for extensibility and sharing in the future.

Literature reveals a trend towards an Indigenous approach to planning, as noted by Paci et al. (2002). Indeed, there are social, cultural, economic and ecological aspects of planning the landscape (Stevenson & Webb, 2003) and there is an increasing effort to understand this complexity to a greater extent by working to integrate Indigenous concerns in land use planning (Houde, 2007). According to Wolfley, cultural values and diversity should be reflected in planning (as cited in Paci et al., 2002). For example, Simpson (2008) writes that traditional Nishnaabeg decisions about land use reflected a concern for the next seven generations. In these ways, it is evident that Indigenous models and visualizations of land use planning are founded upon Indigenous Knowledge systems and view points and are very challenging to depict in current GIS and mapping languages and processes. Through a temporal extension of the one case we are using to show this prototype ontology, via connection with other land use databases for the region gathered in 1997 and then in 2002, 2006, 2008 and 2010 we have also attempted to show this change in land use, knowledge and relationship to environment in one location over time.

We see the ontology as a socio-technical system. It is critical that Indigenous Knowledge is represented and communicated in a way that is true to its original cultural and traditional conceptualization and thinking, rather than simply 'fitting' knowledge into existing scientific or anthropological frameworks of seeing or understanding the environment around us. Innovative use of visualization techniques can contribute to more appropriate representations of Inuit Knowledge. To realize the benefits of this approach, it was apparent to us through the life of this project that knowledge holders must be fully engaged in the ontology creation and visualization process. Such engagement helps prevent the re-colonization possible when Inuit Knowledge is transformed to make it more 'digestible' by others who are not knowledge holders themselves. The prototype system developed through this research has the ability to visualize concepts as well as maps together, providing a platform for a more holistic representation of Indigenous Knowledge for all users.

CONCLUSION

This project has developed a Nunatsiavut geospatial ontology of aspects of the land and environment in the region. Using the thematic foci of Inuit land use and caribou in the region south of Nain, Nunatsiavut, this project has developed a prototype visualization tool for accessing and interacting with the Inuit Knowledge gathered and accessible on these topics. This ontology and visualization prototype provide a foundation for the further maturation of such tools to support decision making on environmental issues by the Nunatsiavut Government in the future. Further, it is expected that this project will make contributions to a growing Indigenous geospatial ontology literature as well in providing an Inuit example from the rapidly changing Canadian Arctic and information as to the engagement of Inuit Knowledge holders and their interests in this process.

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COMMUNITY-DRIVEN RESEARCH ON *H. PYLORI* INFECTION IN THE INUVIALUIT SETTLEMENT REGION

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ABSTRACT

Despite limited systematic data on its presence in northern Canada, *Helicobacter pylori* infection has been an emerging health concern in northern Aboriginal communities, where people are becoming aware of its health risks. In many such communities, people worry about the link between *H. pylori* and stomach cancer, a cancer that occurs more frequently in this region than on average across Canada. Physicians in the North view this infection as a major challenge because it is found in many patients with common stomach complaints and standard treatment is often ineffective in this setting. Health authorities have identified the need for research aimed at developing *H. pylori* control strategies appropriate for the north. This research program seeks to generate knowledge about how health care decision makers can effectively manage *H. pylori* infection in a manner that addresses community concerns. To achieve these goals, the applicants formed the Canadian North *Helicobacter pylori* (CAN*Help*) Working Group, a collaborative team that links the University of Alberta with northern health officials and community organizations. While the research goals require data from multiple northern settings, the team conducted a pilot project as a starting point in Aklavik, NWT, where they found that 61% of participants had *H. pylori* infection, and among those infected, there was a high prevalence of precancerous stomach conditions. This research program, developed at the request of the Inuvialuit Regional Corporation, aims to: 1) Expand the research to additional communities in the Inuvialuit Settlement Region to obtain representative data required for developing regional public health strategies pertaining to *H. pylori* infection; 2) Identify cost-effective and culturally appropriate *H. pylori* management strategies for northern communities; 3) Create knowledge exchange strategies to help community members understand *H. pylori* health risks and currently available solutions.

KEY MESSAGES

- Health risks from *H. pylori* infection include chronic digestive problems, stomach ulcers and in rare instances, stomach cancer.
- Chronic *H. pylori* infection induces chronic inflammation of the stomach lining, gastric atrophy and intestinal metaplasia, which are all associated with increased risk of stomach cancer.
- Communities in the Inuvialuit Settlement Region (ISR) are concerned about health risks from *H. pylori* infection.
- Community leaders seek research to understand the health risks and develop locally appropriate strategies for reducing these risks throughout the Inuvialuit Settlement Region.
- The Canadian North *Helicobacter pylori* (CAN*Help*) Working Group formed to link University of Alberta investigators with northern community leaders and health care providers in the conduct of research aimed at addressing community concerns about health risks from *H. pylori* infection
- The Aklavik *H. pylori* Project, the initial project of the CAN*Help* Working Group, observed that:
  - » Of 333 participants screened for *H. pylori*, 58% tested positive.
  - » Around 90% of *H. pylori*-positive participants (with gastric biopsies that revealed *H. pylori* organisms) had moderate to severe inflammation of the stomach lining.
  - » Of the treatments for eliminating *H. pylori* that were investigated in Aklavik, early results show that a 4-drug regimen is better than the 3-drug regimen most commonly used in Canada to treat *H. pylori* infection (HP-Pac), but we need more data to be sure about the magnitude of the difference.
  - » Treatments for eliminating *H. pylori* are burdensome and more research is needed to find out how to make the treatments less burdensome and more effective.
  - » Follow-up *H. pylori* testing in Aklavik suggests that most people who were successfully treated remained *H. pylori*-free during the next 2-3 years.
  - » Our research so far has not pinpointed an environmental source of *H. pylori* in Aklavik or other northern Canadian communities where *H. pylori* projects are being carried out; this is consistent with findings of research around the world: the evidence suggests that most people with *H. pylori* infection get it from direct contact with a person who has the infection.
- Information from additional northern communities is needed to fulfill the CAN*Help* Working Group research goals.
- The Inuvialuit Regional Corporation (IRC) asked the CAN*Help* Working Group to expand the research to additional ISR communities.
- At the request of the IRC, the University of Alberta researchers of the CAN*Help* Working Group and the IRC executed a written research agreement for the ISR *H. pylori* Project.
- The ISR *H. pylori* Project was launched in Tuktoyaktuk in February 2011.
- To date, 107 Tuktoyaktuk residents consented to participate in the ISR *H. pylori* Project; 91 participants completed questionnaire-based interviews; 104 were tested for *H. pylori* infection (proportion positive: 57%); 13 consented to upper gastrointestinal endoscopy, 13 had biopsies for culture and histopathology obtained, 29 have been assigned treatment and 15 enrolled in the treatment trial.
- Long-term follow-up is ongoing in Aklavik and Tuktoyaktuk, as is analysis of questionnaire data and reporting research results back to the community.

- Community presentations were carried out throughout the ISR in 2014. The communities of Ulukhaktok, Paulatuk and Sachs Harbour were informed about current findings about *H. pylori* in the north and research opportunities that they can take part in. Expansion of the ISR *H. pylori* Project to other communities is under way.

OBJECTIVES

Helicobacter pylori infection, linked to peptic ulcer disease and stomach cancer, is a health concern in northern Aboriginal communities, where people are aware of its health risks. Health care providers in the north view this infection as a major challenge because it is found in many patients with common stomach complaints and standard treatment is often ineffective in this setting. This research program seeks to generate knowledge about how health care decision makers can effectively manage *H. pylori* infection in a manner that addresses community concerns. While the research goals require data from multiple northern settings, the team conducted a pilot project as a starting point in Aklavik, NWT, where they found that a high prevalence of *H. pylori* infection, and among those infected, a high prevalence of precancerous stomach conditions.

This research program aims to:

1. Expand the research to additional communities in the Inuvialuit Settlement Region to obtain representative data required for developing regional public health strategies pertaining to *H. pylori* infection;
2. Identify cost-effective and culturally appropriate *H. pylori* management strategies for northern communities; and
3. Create knowledge exchange strategies to help community members understand *H. pylori* health risks and currently available solutions.

INTRODUCTION

Helicobacter pylori infection has been a health concern in some northern Aboriginal communities, where people are aware of its health risks. In many such communities, people worry about the link between *H. pylori* and stomach cancer, a cancer that is more common in this region than on average across Canada. Northern health care providers see this infection as a challenge because it is found in many patients evaluated for stomach complaints, but treatment in this region is often ineffective. Public health authorities have identified the need for research to develop locally appropriate *H. pylori* control strategies.

This research program was developed at the request of the Inuvialuit Regional Corporation (IRC) on behalf of communities in the Inuvialuit Settlement Region (ISR) of western Canada. The goal is a comprehensive investigation of *H. pylori* infection in ISR communities so that such communities are represented in a broader research agenda that aims to develop public health strategies for *H. pylori* infection in northern Canada. This research seeks to generate knowledge about how northern health authorities can manage *H. pylori* infection in a manner that addresses community concerns about health risks. To achieve these goals, the research team formed the Canadian North *Helicobacter pylori* (CAN*Help*) Working Group to link northern community organizations and health officials with University of Alberta researchers.

To develop this research, the CAN*Help* team initiated a pilot project in Aklavik, NWT, focused on: investigating the burden of disease and risk factors associated with *H. pylori* infection in the Aklavik population; identifying effective therapies; and developing knowledge exchange strategies that address community concerns. This preliminary research has shown that 58% of Aklavik's project participants had *H. pylori* infection, and among those infected there was a high prevalence of severe inflammation and precancerous lesions in the stomach. In a trial to compare standard treatment against a new regimen in 89 people who had not been treated before, cure rates were 70% of 40 on sequential therapy and 50% of 49 on standard therapy, a study size too small for precise estimates of the treatment effect size.

To generate study results with greater certainty, the CAN*Help* research program needs a larger number of participants representing additional northern communities. In addition to ISR projects, we have been conducting similar research in Old Crow, YT since 2010 and Fort McPherson NT since 2012. We have been working with the IRC since January 2010 on the expanding the research initiated in Aklavik to the remaining Inuvialuit Settlement Region communities.

This research addresses a health problem that imposes a disproportionate burden on northern communities relative to other groups in Canada. It aims to improve the management of *H. pylori* infection in northern communities, and reduce corresponding health risks. The research design conforms to principles of community-based participatory research, incorporates innovative approaches to knowledge exchange, and adheres to the ACUNS Ethical Principles for the Conduct of Research in the North and CIHR Guidelines for Health Research Involving Aboriginal People. The effectiveness of this research will be enhanced by the collaborative research team that links scientists across a comprehensive set of scholarly disciplines with decision-makers, industry partners, and community groups toward the common goal of improving community health.

ACTIVITIES

Time frame and study area

Fieldwork and knowledge sharing activities were carried out throughout the year in the communities of Aklavik, Tuktoyaktuk, Paulautk, Ulukhaktok, Sachs Harbour, and Yellowknife in the Northwest Territories (NT).

Research

Planning for the expansion of the Inuvialuit Settlement Region (ISR) *H. pylori* Project continued. Community information sessions were held in Paulatuk, Ulukhaktok, and Sachs Harbour, NT to share information on opportunities available through the Canadian North *Helicobacter pylori* (CAN*Help*) Working Group. Our working group also established a part-time Community Partnership Coordinator position in the offices of the Government of the Northwest Territories (GNWT) Division of Aboriginal Health and Community Wellness in Yellowknife, NT. This role will help to develop and share research dissemination materials throughout the territory.

Over the same period, graduate students undertook data collection activities in Aklavik and Tuktoyaktuk, NT. MSc student Kate Williams traveled to both communities to collect antibiotic exposure histories from project participants' medical charts. PhD student Emily Hastings also traveled to Aklavik and Tuktoyaktuk, NT to conduct qualitative semi-structured interviews to help identify research questions for her PhD dissertation work.

In addition to the community information sessions held in Paulatuk, Ulukhaktok, and Sachs Harbour, knowledge sharing activities were undertaken in Aklavik, Tuktoyaktuk, and Yellowknife, NT throughout the year.

During 2014/2015, the following activities were completed:

- Postdoctoral Fellow Arianna Waye and PhD student Amy Colquhoun traveled to Yellowknife, NT where they met with NT Territorial Epidemiologist Heather Hannah to discuss availability of territorial administrative and disease registry data and to present a research update to the Beaufort Delta Health and Social Services Authority.

- Members of the CAN*Help* Working Group met with Evelyn Storr, Director of Community Development for the Inuvialuit Regional Corporation, to discuss project expansion and coordinate a tour of communities in the Inuvialuit Settlement Region.
    - » Ms. Storr and project staff held three community information sessions in Paulatuk, Ulukhaktok, and Sachs Harbour, NT to share information on opportunities available through the CAN*Help* Working Group.
    - » At the meetings, community members were enthusiastic about current opportunities, and attendees in Sachs Harbour expressed an interest in forming a local planning committee to guide project-related activities.
- A Community Partnership Coordinator position was established in the offices of Sabrina Broadhead, Director of the Division of Aboriginal Health and Community Wellness for the GNWT.
    - » Community Partnership Coordinator Sabrina Lakhani is working with members of the CAN*Help* Working Group to develop dissemination materials that can be used throughout the NT, including a video series on *H. pylori* infection and stomach health.
- Two youth involved in our Knowledge Exchange Program (KEP) traveled from Aklavik, NT to our team's offices in Edmonton, AB to share their experience developing materials for educating Aklavik residents about *H. pylori* microbiology research.
    - » Based on feedback from Aklavik residents and the Aklavik *H. pylori* Project Planning Committee, we are currently working to expand our KEP to other communities in the NT.
- Members of the Aklavik *H. pylori* Project Planning Committee also requested that additional approaches to water testing be attempted in order to overcome the limitations of the 2013 pilot project that tested environmental surface water samples and domestic treated water samples for the presence of living *H. pylori* organisms.
    - » Planning will start in spring 2015, with data collection starting mid to late 2015.
- The Chair of the Aklavik Health Committee, Billy Archie, requested that Inuvialuit traditional medicines be tested in our microbiology lab to determine whether they have any inhibitory effects on *H. pylori.*
    - » Planning for this new line of inquiry will start in summer 2015.
- Ethnographic Fieldwork Lead Sally Carraher returned to Aklavik, NT to continue her ethnographic research on the local kinship system and update the Aklavik *H. pylori* Planning Committee on several ongoing projects, including the continuation of the water study, better understanding antimicrobial effects of traditional medicines on stomach health, and the expansion of the knowledge exchange program.
- MSc student Kate Williams traveled to Aklavik and Tuktoyaktuk, NT to collect antibiotic exposure histories from medical charts of participants who had *H. pylori* cultured from stomach biopsies and tested for antibiotic susceptibility and/or were treated and completed a post-treatment breath test.
    - » The information collected will be used to estimate associations of antibiotic exposures on two health outcomes: 1) the prevalence of antibiotic-resistant *H. pylori* infection and 2) success of treatment to eliminate *H. pylori* infection.
- PhD student Emily Hastings traveled to Aklavik and Tuktoyaktuk, NT to conduct qualitative semi-structured interviews with key informants from the communities to identify specific research questions that address predominantly expressed community concerns about the health effects of regular exposure to environmental contaminants

that will become the focus of her PhD dissertation work.

- PhD student Amy Colquhoun coordinated a permanent installation in a University of Alberta building to showcase CAN*Help* Working Group community art generated by project logo contests.
- Postdoctoral Fellow Arianna Waye oversaw literature reviews on the economic costs of peptic ulcer disease and gastric cancer.
- Members of the CAN*Help* Working Group published two papers, one in Gut Microbes, and one in Gut.
    - » Hastings EV, Yasui Y, Hanington P, Goodman KJ, CAN*Help* Working Group. Community-driven research on environmental sources of *H. pylori* infection in arctic Canada. Gut Microbes. 2014; 5(5):606-617.
    - » Colquhoun A, Arnold M, Ferlay J, Goodman KJ, Forman D, and Soerjomataram I Global patterns of cardia and non-cardia gastric cancer incidence in 2012. Gut (in press). 2015.
- Members of the CAN*Help* Working Group published two abstracts, both in Gastroenterology.
    - » Veldhuyzen van Zanten S, Aplin L, Chang HJ, Morse AL, Lazarescu A, Girgis S, Goodman KJ. Community-Driven Research on *Helicobacter pylori* Infection in the Canadian Arctic: the Fort McPherson *H. pylori* Project. Gastroenterology. 2014; 146 (5):S-183
    - » Veldhuyzen van Zanten S, Aplin L, Chang HJ, Morse AL, Lazarescu A, Girgis S, Keelan M, Goodman KJ. Community *H. pylori* Project Treatment Trial Results From the Canadian Arctic. Gastroenterology. 2014; 146 (5):S-400.
- Graduate students and staff of the CAN*Help* Working Group delivered presentations at 4 international conferences, 2 national conferences, 1 provincial conference, and 4 campus conferences.
- Graduate student Emily Hastings was awarded first place in the student poster competition for her presentation of her CAN*Help* Working Group research at the at the World Congress of Epidemiology in Anchorage, Alaska.

RESULTS

In total, 376 people have participated in the Aklavik *H. pylori* Project; thus the project has included over 60% of the Aklavik population (~600). To date, the project has yielded data on clinical factors from 345 participants, individual-level socio-environmental factors from 285, household-level socio-environmental factors from 145 households, results of breath tests for detection of *H. pylori* infection from 333 participants (positivity=58%) and gastric biopsies from 194 who underwent endoscopy. Pathological examination of gastric biopsies focused on assessing the presence of abnormalities known to indicate increased risk of stomach cancer: chronic gastritis; gastric atrophy; and intestinal metaplasia. Of 129 participants with *H. pylori* detected by examination of gastric biopsies, 43% had severe gastritis and 47% had moderate gastritis, while 21% had gastric atrophy and 11% had intestinal metaplasia. Biopsies were also processed for culture of *H. pylori* and isolated strains were tested for antibiotic susceptibility: 25% of 120 *H. pylori* isolates tested were resistant to one drug and 7% were resistant to more than one drug. Antibiotic susceptibility results were taken into account for assignment of treatment regimen in our clinical trial component. The Aklavik trial showed that the standard therapy (a proton pump inhibitor, amoxicillin and clarithromycin for 10 days) used across Canada achieved cure in only 59% of Aklavik participants randomized to this treatment, in contrast to 80% effectiveness observed on average in Canada. A follow-up study was done in Aklavik to investigate the incidence rate of new cases of *H. pylori* infection and rates of reinfection in successfully treated participants. The incidence rate combining new cases and reinfections was estimated at 2.1% per year among participants aged 15 and older.

The ISR *H. pylori* Project started in Tuktoyaktuk with 107 participants. To date, this project has yielded data on clinical factors from 91 participants, individual level socio-environmental factors from 79, household-level socio-environmental factors from 60 households, results of breath tests from 104 participants (positivity=57%) and gastric biopsies from 13; 29 project participants have been assigned treatment, and 15 of them were enrolled in the treatment trial. With resources from other grants, the research team has conducted similar community projects in Old Crow, YT since 2010 and Fort McPherson, NT since 2012. The information from these two Gwich'in communities provides a basis for comparison with the Inuvialuit communities that are the focus of the ArcticNet project.

The Old Crow *H. pylori* Project enrolled 202 participants - around 80% of the Old Crow population (~250). To date, this project has yielded data on clinical factors from 138 participants, individual-level socio-environmental factors from 138, household-level socio-environmental factors from 86 households, results of breath tests from 194 participants (positivity=68%) and gastric biopsies from 63. Of 57 participants with *H. pylori* detected by examination of gastric biopsies, 65% had severe gastritis and 32% had moderate gastritis, while 74% had gastric atrophy and 35% had intestinal metaplasia. Due to the low effectiveness of standard treatment observed in Aklavik, the treatment trial for the Old Crow project used two alternative treatments: sequential therapy (a combination of a proton-pump inhibitor and amoxicillin for Days 1-5 and a proton-pump inhibitor, clarithromycin and metronidazole for Days 6-10); and quadruple therapy (a combination of a proton-pump inhibitor, Pepto-Bismol, metronidazole and tetracycline for 10 days). In this trial, a larger proportion of participants in the quadruple therapy group were treated successfully, but more data is needed for a precise estimate of the difference in treatment effectiveness of the alternate regimens. Taken together, our trials show a greater frequency of successful treatment among participants who had better adherence to the treatment regimen.

The Fort McPherson *H. pylori* Project has enrolled 236 participants since it launched in June 2012. To date, the project has yielded data on clinical factors from 175 participants, individual-level socio-environmental factors from 154, household-level environmental factors from 121 households, results of breath tests from 228 participants (positivity=59%) and gastric biopsies from 53 participants. Of 37 participants with *H. pylori* detected in gastric biopsies, 38% had severe gastritis and 54% had moderate gastritis, while 70% had gastric atrophy and 14% had intestinal metaplasia. The treatment phase of the Fort McPherson *H. pylori* Project is in progress and has enrolled 68 participants as of February 2015.

Our research suggested a potential gap between the views of participants and researchers on health concerns about *H. pylori* infection. Participants appeared to have little information about *H. pylori* infection occurring in populations all over the world, not only in the north. Many participants did not realize research activities were still carried out when researchers were not present in the community. Basic knowledge of micro-organisms and genetics was also unfamiliar to many northern residents. At the same time, researchers had limited awareness of how community members understand determinants of health in general, and determinants and consequences of infectious diseases such as *H. pylori*, in particular. To fill in these gaps, a knowledge exchange program (KEP) was developed collaboratively with two young women from Aklavik. Researchers traveled to Aklavik to learn from participants, and the two young women from Aklavik participated in research activities conducted by public health researchers and gastroenterologists at the University of Alberta. They also applied microbiology methods used to study characteristics of the *H. pylori* bacteria and learned how to interpret the results. Upon returning to Aklavik, they presented what they learned to other community members, including high school students. The KEP built youth capacity in the community and allowed the dissemination of research results in a meaningful and culturally appropriate way.

DISCUSSION

Our research has estimated a high prevalence of *H. pylori* infection in Aklavik (58%), Old Crow (68%), Tuktoyaktuk (57%) and Fort McPherson (59%). We have also observed high prevalence of severe gastric inflammation in people with *H. pylori* infection, and a pattern of *H. pylori*-associated stomach disorders that indicates increased risk of stomach cancer. These findings confirm that community concerns about health risks from *H. pylori* infection are warranted.

Preliminary findings from our treatment trials show that the standard 3-drug therapy has poor effectiveness and an alternate, though more complex, 4-drug therapy may be more effective in the participating communities. While more data is needed for precise estimates of the treatment effectiveness of investigated treatment regimens, we have shown the need for changes in clinical practice pertaining to the treatment of *H. pylori* infection in the region.

Many factors influence *H. pylori* infection and disease risk in Arctic Aboriginal communities. Analysis of data collected to date confirms the need to increase participation in this research program so that informative statistical analyses can be carried out. Results from gastric biopsy data showed important intercommunity differences in *H. pylori* disease burden, even between closely related communities such as Aklavik, Old Crow and Fort McPherson. The different distributions of these disorders across the communities confirm the importance of obtaining additional data from multiple communities in the region.

The continuing development and expansion of our community *H. pylori* projects has allowed our team to develop expertise in research agreements between scientists and communities. This may serve as a model for future community-based participatory research in health science. Our research also developed a knowledge exchange program (KEP) that permits the dissemination of research results in a meaningful and culturally appropriate way to community members. The KEP fosters a strong community-researcher partnership and builds youth capacity in northern communities. It will be used as a framework for future knowledge exchange activities in other communities to help northern residents understand *H. pylori* health risks as well as currently available solutions and unsolved challenges for reducing these health risks.

CONCLUSION

Our research has estimated a high prevalence of *H. pylori* infection in Aklavik, Tuktoyaktuk and Ft. McPherson, NT and Old Crow, YT. We have also observed high prevalence of severe gastric inflammation in people with *H. pylori* infection, and a pattern of *H. pylori*-associated stomach disorders that indicates increased risk of stomach cancer. These findings confirm that community concerns about health risks from *H. pylori* infection are warranted. Our initial research in Aklavik provided a good start toward generating the information needed for developing regional public health strategies for reducing health risks from *H. pylori* infection. Analysis of data collected from other communities provides a strong rationale for the need to expand this research to additional communities. Our continued progress toward including additional communities in this research is allowing us to accumulate data from diverse Arctic communities. This will allow us to generate sufficient information conduct policy analysis to identify cost effective *H. pylori* management strategies that are ethically, economically, and culturally appropriate for northern communities.

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INTERNATIONAL INUIT COHORT STUDY: DEVELOPING THE NEXT PHASE

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ABSTRACT

The International Inuit Cohort Study (IICS) was born from an international collaborative effort to gather pertinent data from Inuit circumpolar populations in order to identify differences and trends in this population. This cohort study addresses long-standing questions with respect to Inuit health research. Many studies among Inuit populations are limited by a lack of statistical power, weak external validity and absence of temporal links and causality between disease and potential etiologic factors. Indeed, the small size of communities (between 50 and 5000) living in different regions of the Arctic limit the use of epidemiological studies to determine rates of health outcomes. This initiative is based on three different companion studies conducted among Inuit adults in Canada and Greenland. Each study has a cross-sectional and a longitudinal component. The protocols used were developed in close collaboration and are very similar. The baseline surveys were carried out among adults (≥18 years) with Inuit/Yupik ancestry in the Canadian Arctic and Greenland. From 2004 to 2010, a total of 6223 individuals were recruited as part of three surveys: Qanuippitaa? How are we? Nunavik Inuit Health Survey 2004 (n=929); Inuit Health in Transition-Greenland Survey 2005-2010 (n=3108); and the International Polar Year-Inuit Health Survey (IPY-IHS) in Nunavut, Inuvialuit Settlement Region, and Nunatsiavut 2007-2009 (n=2459). Individuals participated in 3-4 hour sessions, including answering to interviewer- and self-administered English/Inuktitut questionnaires to ascertain a range of various lifestyle habits and health outcomes, and to medical and para-clinical examination (with biological samples drawn). At the outset, the IICS project was conducted across the three inhabited ArcticNet IRIS regions in Canada, and extended to Greenland. IICS deals with all aspects of the Cohort, including its constitution as a databank and all activities to further gather data to augment the databank. It builds on previous work on the vulnerabilities of Arctic communities, and it is feasible because of established collaborations with northern people and organizations. The project documents the changing physical, biological and socioeconomic conditions that are affecting people across the circumpolar North and identifies policies and strategies to assist communities in dealing with these changes. However, an agreement has yet to be reached between Inuit regions involved in the IPY-Inuit Health Survey (and especially Nunavut) and principal investigators regarding the governance of data from this survey. Therefore, the work for 2014-2015 involved data analyses only from the Nunavik and Greenland health surveys. In recent years of the project, a new component of the Inuit Cohort Study has emerged focussing on the social determinants of Inuit health, among which community and housing conditions. This component follows three objectives: 1) documenting associations between communities' socioeconomic conditions and health in Nunavik and Greenland; 2) documenting associations between household overcrowding and psychosocial health in Nunavik and Greenland; and 3) assessing the impacts of moving to a new house for Inuit health and well-being in Nunavik and Nunavut. Note: Following the tragic passing of Eric Dewailly in June 2014, Mylène Riva was named Principal Investigator of this project.

KEY MESSAGES

- An international integral data platform supporting cross-disciplinary research in the Inuit circumpolar region was completed in 2014, and has been operational since. However, only query data from two of the Inuit health survey datasets, i.e. Nunavik and Greenland, has been enabled. This data repository consists of a total of 253 variables (191 harmonized data and 62 newly created data) among 3764 individuals across Greenland and Nunavik. Access to data for Nunavut, Nunatsiavut, and Inuvialuit Settlement Region collected as part of the IPY-IHS will be enabled once an agreement has been reached.
- There are several projects of data analysis underway using data from IICS for both Nunavik and Greenland, or for either Nunavik or Greenland.
  - In one project, we are examining whether poor self-rated health (SRH) is associated with objective (clinical) health indicators among Inuit in Nunavik and Greenland. Results show that poor SRH is associated only with impaired fasting glucose among participants from Greenland, and with higher waist circumference among participants from Nunavik. In sex-specific analyses, poor self-rated health was associated with impaired fasting glucose and with higher waist circumference among women in Greenland, but not among men. In Nunavik, poor self-rated health was associated with higher waist circumference among men only. Associations between SRH and selected objective health measurements are not consistent. The next step of this project is to assess whether SRH predicts mortality.
  - We are examining the influence of community conditions in relation to blood pressure in Greenland, and obesity in Nunavik. Adjusting for age, sex, individuals' socioeconomic circumstances and known risk factors, higher blood pressure and elevated risk of obesity are observed in communities characterised by less favorable socioeconomic conditions.
  - In another project, we are assessing whether socioeconomic position (SEP) is associated with the incidence of cardiovascular diseases (CVD) among Inuit in Nunavik, Canada, independently of traditional risk factors. Results show that the odds of being diagnosed with a CVD are significantly higher among people with lower SEP at baseline, independent of clinical and behavioral risk factors.
- We are planning the follow-up to the Nunavik Inuit Health Survey to be conducted in 2016. Workshops and meetings have been conducted in Quebec City and Kuujjuaq. We have submitted a research proposal to ArcticNet's Phase 4 competition, which has been funded.

The research project "*Housing in the Canadian Arctic: Assessing the health impacts of rehousing for Inuit families*" has received funding from the Canadian Institutes of Health Research ($199,846, 2014-2016) and by ArcticNet Phase 4 ($480,255, 2015-2018). Data collection of the research project was conducted in October 2014. We recruited 135 participants across six communities in Nunavik. Data analysis is planned to start in April 2015.

OBJECTIVES

1. Finalize the documentation to access data from the IICS. Update the website. Analyze data from the IICS, either the fully-merged data from the Nunavik and Greenland surveys or independent studies from using data from these two surveys in a comparative perspective.

2. Prepare the 2016 follow-up of the Nunavik Inuit Health Survey (Exploratory research;

meetings, workshop and planning; ongoing collaboration).

3. Expand ongoing research on community and housing conditions in relation to Inuit health.

Note: Since the project "*International Inuit Cohort Study: Developing the next phase*" is coming to an end in 2015, there are no long-term objectives.

INTRODUCTION

Several studies have documented inequality in health status for Inuit populations in comparison with other populations. In Canada, Inuit populations generally experience poorer health status (e.g. mortality, morbidity and health perception measures) compared to non-Indigenous Canadians. Demographically they are susceptible to a greater extent to disadvantages associated with having a very young demographic profile for they are the youngest population in Canada (i.e. resource and infrastructure pressures including housing). Finally, the study of biomarkers (e.g. blood pressure, fatty acid signatures, environmental contaminant, body burdens, etc.) also contribute to understanding and describing the scenario of epidemiological transition among Inuit populations, indicating the possible (even likely) onset of a chronic disease epidemic (cardiovascular, diabetes) triggered by a shift in traditional lifestyle and diet towards more sedentary lifestyle in which market foods are much more present in the diet.

The International Inuit Cohort Study (IICS) is a composite of three cross-sectional health surveys conducted in Canada and Greenland between 2004 and 2009, creating the largest databank for Inuit health to date. Chronologically the first survey, "Qanuippitaa? How are we? Nunavik Inuit Health Survey" was conducted in all 14 communities in Nunavik in 2004 (929 adult participants). The second took place over a period of 4 years in 22 out of 80 communities in Greenland (2005-2009, 2834 adult participants), the "Inuit Health in Transition-Greenland Study". Finally, the International Polar Year Adult Inuit Health Survey (IPY-IHS) conducted in 2007-2008 covers all communities in Nunavut, Nunatsiavut and Inuvialuit (2595 adult participants). All participants have provided consent to be contacted for follow-up investigation, and thus have consented to be part of the International Inuit Cohort. A web site at http://circumpolarcohort.crchuq.ca/index.htm provides further information. Since then, the follow-up of the Greenland cohort has been completed in 2014. The Nunavik cohort will be followed-up in 2016.

The three surveys have pursued common goals and have adopted similar methods focused on measuring the epidemiological transition of Inuit populations and the pursuit of knowledge to inform: the risks and benefits of key aspects of this transition as well as improving health outcomes (e.g. chronic diseases, self-inflicted injuries). The information gathered from participants over the course of the field operations have included variables that represent the determinants of health (e.g. food security and nutrition; education; employment; revenue; housing; culture; social support, and more), demographic information, and health outcomes information (perceived health status; clinical health status) for the populations of these Inuit regions. It is important to collect baseline health status data and their relationship to environmental factors including contaminants and lifestyle among Inuit communities in the circumpolar region.

In 2014, an integral data platform for the three heterogeneous, cross-disciplinary and multi-scale datasets collected from the three surveys was finalized. Its structure provides an excellent opportunity for extension with the future follow-up of the three existing cohort studies. In addition, several research activities have been conducted in order to better document socio-environmental factors, such as housing and community conditions, associated with Inuit health. An agreement has yet to be reached between Inuit regions involved in the IPY-Inuit Health Survey (Inuvialuit Settlement Region, Nunavut and Nunatsiavut) and principal investigators regarding the governance of the data from this survey. It has recently been decided that until an agreement has been reached, data from the IPY-IHS cannot be accessed or analyzed, for any projects.

ACTIVITIES

Objective 1: IICS – data analysis

Several statistical analyses using data from the independent studies composing the IICS, but analysed in a comparative perspective, were conducted and published in peer-reviewed journals in 2014, as listed below. In addition, our team presented their work at national and international conferences.

Forthcoming articles

- Riva M., Ruiz Castell M., et al. Socioeconomic inequalities in the incidence of cardiovascular diseases among Inuit in Canada: Prospective analysis of the Nunavik Inuit Health Survey 2004-2011.
- Riva, M., Lytken Larsen, C.V., Bjerregaard, P. Social and geographic inequalities in blood pressure among Inuit in Greenland.
- Ruiz-Castell M, Laouan-Sidi EA, Déry S, Riva M. Individual and Community-level determinants of Obesity in Nunavik.
- Baron, M., Riva, M., Dahl-Petersen, I., Lytken Larsen, C.V., Bjerregaard, P. Association between selected health outcomes and risk factors and self-rated health in Nunavik and Greenland.
- Philibert A., Bjerregaard P, Dewailly E, Young TK, Chan HM. An Integral Data Platform for three Databases from Inuit Health Surveys conducted in Greenland and Canada.

Peer-reviewed scientific publications published in 2014-2015

- Riva, M., Lytken Larsen, C.V., Bjerregaard, P. Household crowding and psychosocial health among Greenlandic Inuit. International Journal of Public Health. 2014; 59: 739-748.
- Riva, M., Plusquellec, P., Juster, R.P., Laouan-Sidi, E.A., Abdous, B., Lucas, M., Déry, S., Dewailly, E. Household crowding is associated with higher allostatic load among Inuit. Journal of Epidemiology and Community Health. 2014, 68:363-369.

Conference presentations in 2014-2015

- Dewailly, E., Ayotte, P., Muckle, G., Riva, M., Lucas, M., Lemire, M. 25 years of scientific progress on contaminants and health in the Arctic. Arctic Frontiers 2014, Tromso, Norway, 19-25 January 2014.
- Riva, M., Lucas, M., Lemire, M., Dery, S., Dewailly, E. Socioeconomic position and incidence of cardiovascular diseases among Inuit in Nunavik, Canada. 142nd American Public Health Association Annual Meeting and Exposition, New Orleans, LA, USA. November 2014.
- Riva, M. How do housing conditions get under the skin to influence health? Considering psychosocial factors associated with the house environment in the Arctic. International Congress of Arctic Social Sciences. Prince George, BC, Canada. May 2014.
- Riva, M. Conditions des logements et santé dans l’Arctique: le rôle des facteurs psychosociaux. 19e Congrès d’études Inuit – 19th Inuit Studies conference. Qaumaniq: Le savoir qui illumine – Enlightening Knowledge. Quebec City, QC, Canada, October 2014.
- Baron, M., Riva, M., Dahl-Petersen, I., Lytken Larsen, C.V., Bjerregaard, P. État de santé autoévalué, santé objective et inégalités sociales

chez les Inuit du Nunavik et du Groenland. 19e Congrès d'études Inuit – 19th Inuit Studies conference. Qaumaniq: Le savoir qui illumine – Enlightening Knowledge. Quebec City, QC, Canada, October 2014.

- Riva M., Goldhar, C. T48. We Don't Need Housing, We Need Homes: Social, Economic, Environmental, Cultural, Health and Well-Being Dimensions of Housing Needs in the Arctic. Arctic Change Conference, Ottawa 8-12 December 2014.
- Ruiz-Castell M, Riva M. The Social Determinants of Health in Nunavik: exploring gender inequalities.

Objective 2: Prepare the 2016 follow-up of the Nunavik Inuit Health Survey

Designing and implementing the Nunavik Health Survey Qanuippitaa 2016; Funding organization: ArcticNet; Named Principal Investigator (PI): Pierre Ayotte; Co-Principal investigators (PI): Gina Muckle, Mylène Riva, Michel Lucas, Mélanie Lemire, Benoit Lévesque; Total funding: $546,258, 2015-2018.

Our team was successful in getting a grant proposal funded by ArcticNet to prepare the follow-up of the Nunavik Inuit Health Survey. In collaboration with the Nunavik Regional Board of Health and Social Services (NRBHSS; who has already invested money in the survey) and Social Services and Institut National de Santé Publique (INSPQ), who are core leaders of the survey, we are seeking additional funding from the Ministère de la santé et des services sociaux.

Planning activities have started in 2014 and will intensify in 2015:

Frequent meetings involving PIs, and colleagues from NRBHSS and INSPQ, are being held to discuss research objectives, content of the survey, and survey tools.

The 2016 survey is expected to comprise three components: an adult cohort (same participants as in 2004); a youth cohort (18-29 years of age); and a community component assessing community health and well-being. The survey is being developed within a participatory research framework, where the research team, organisation partners, and community members collaborate to set-out goals and objectives of the survey.

We held a first workshop in Kuujjuaq on January 27-28 2015 in Kuujjuaq with co-researchers, local partners and community members to discuss values, principles, and methodological approaches to guide the development of the survey.

Objective 3: Expand ongoing research on housing and community conditions

Mylene Riva was awarded a young investigator award to pursue her research program "*Monitoring social inequalities in Indigenous health: documenting the social determinants of health at the individual, household, and community levels to support the formulation and implementation of social policies and programs*" (Fonds de recherche du Québec; $306,321; 2014-2018). Funds from this grant support her work on further examining the role of community and housing conditions in influencing Inuit health and well-being using data form the IICS (Nunavik and Greenland).

Mylene Riva is also the PI of the project "*Housing in the Canadian Arctic: Assessing the health impacts of rehousing for Inuit families*" which has been funded by the Canadian Institutes of Health Research (CIHR)-Population Health Intervention Research ($199,896, 2014-2016). An extension of this project was submitted to ArcticNet Phase 4 competition (Housing, health, and well-being across the Arctic: Regional, local, and family perspectives), and received funding ($480,125, 2015-2018).

The objective of this project is to asses the health and well-being impacts of moving to a newly built social housing unit in Nunavik and Nunavut. Baseline data collection from the housing project (supported by CIHR) was conducted in 6 communities Nunavik, where new houses were to be built. In October-November 2014, households, women and men over 18 years old on the waitlist for social housing were invited to participate in this study. Using questionnaires, we collected data on: housing conditions (including crowding and structural quality), general and respiratory health, psychological health and psychosocial factors. We recruited 135 participants, for a response rate of 70%. Participants will be interviewed about 15 months after moving into the new house.

Baseline data collection will be conducted in three communities in Nunavut in May 2015, and in a further three communities in early Fall 2015; communities in Nunavik and Nunatsiavut will be added in the Fall 2015.

RESULTS

Related to Objective 1 – IICS data analysis

Abstracts for the articles are presented.

Philibert A., Bjerregaard P, Dewailly E, Young TK, Chan HM. An Integral Data Platform for three Databases from Inuit Health Surveys conducted in Greenland and Canada.

- **Background**: It is important to collect baseline health status data and understand their relationship to environmental factors including contaminants and lifestyle among Inuit communities in the circumpolar region. Three independent cohort studies were conducted: (1) the 2004 Nunavik Cohort Study in Canada; (2) the International Polar Year (IPY) Adult Inuit Health Survey (HIS) 2007-2008 in Canada; and (3) the Inuit Health in Transition 2005-2010 in Greenland.
- **Objectives**: The overall objective is to develop an integral data platform for the heterogeneous, cross-disciplinary and multi-scale datasets collected from the three cohort studies.
- **Methods**: Data harmonization procedures were used to adjust for differences and inconsistencies among data definition, format and methods to make the data mutually compatible. A total of eight different techniques were used for converting data during the harmonization process.
- **Results**: The three databases have a combined total of 4288 parameters ((1)=2499 + (2)=1024 + (3)=765), of which only 227 are paired. Among the 227 parameters, 79 showed a complete match whereas 143 were partially matched. A total of five matches were found impossible. The newly developed data platform consists of data collected from a total of 6777 participants from the three cohort studies conducted between 2004 to 2010. It consists of a combined total of 222 parameters that can be classified into 10 different categories including: 1) health status (32); blood contaminant concentrations (57); clinical tests (39); clinical biochemistry (35); lifestyle (14); socio-demographic characteristics (13); mental health (12), food use pattern (10), social networks (6) anthropometry (4).
- **Discussion**: The harmonization of data resulted in some loss precision and information for each data set but the integral data platform will enable robust and efficient cross-national comparative research on Inuit health.
- **Conclusion**: The development of such a data platform from existing cohort studies can serve as a template for other regions and will facilitate the development of regional and international policies to promote health.

Baron, M., Riva, M., Dahl-Petersen, I., Lytken Larsen, C.V., Bjerregaard, P. Association between selected health outcomes and risk factors and self-rated health in Nunavik and Greenland.

- **Background**: Self-rated health (SHR) has been found to be an indicator of mortality and morbidity in different populations worldwide, and is widely used as a measure of health status in population health surveys. However, few studies have examined SRH in relation to objective health measures among Indigenous populations in the circumpolar area. The objective of this study is to assess if SRH is associated with objective health measures in Nunavik and Greenland and to identify whether associations differ between men and women.
- **Methods**: Cross-sectional comparable data among adults (18+ years) from the Nunavik Inuit Health Survey (2004) and Inuit Health in Transition Greenland Study (2005-2010) were analyzed. SRH was dichotomized into good health (excellent, very good or good health) vs. poor health (fair and poor health). Age-adjusted logistic regression models were used to examine associations between SRH and several clinical health measures: waist circumference, diabetes (impaired fasting glucose), blood pressure, and cholesterol. Analyses were stratified by sex and conducted separately for the two surveys.
- **Results**: In the overall regional samples, poor SRH was associated only with impaired fasting glucose among participants from Greenland, and with higher waist circumference among participants from Nunavik. In sex-specific analyses, poor SRH was associated with impaired fasting glucose and with higher waist circumference among women in Greenland, but not among men. In Nunavik, poor SRH was associated with higher waist circumference among men only.
- **Conclusions**: Associations between SRH and objective health measures provided mixed and sex-specific results. More in depth analyses are needed to understand associations between SRH and other health measures with relevance for clinical practice and preventive strategies, and to assess the strength of SRH in predicting mortality among Inuit populations.

Riva, M., Lytken Larsen, C.V., Bjerregaard, P. Household crowding and psychosocial health among Greenlandic Inuit. International Journal of Public Health. 2014; 59: 739-748.

- **Objective**: Poor housing conditions experienced by many Indigenous peoples threaten their health and well-being. This study examines whether household crowding is associated with poorer psychosocial health among Greenlanders, and the mediating role of social support. It also assesses whether Inuit men and women are differently influenced by their housing conditions.
- **Methods**: Data on more than 3000 Inuit aged 18 years and older are from the Inuit Health in Transition Greenland Survey. Associations between household crowding and composition, and mental well-being and binge drinking were examined using logistic regression models, adjusting for individuals' characteristics.
- **Results**: Household crowding was associated with poorer mental well-being. Binge drinking was more common among people living in households without children. These effects were more important for women than for men. The association between household crowding and mental well-being was significantly mediated by social support. This suggests that having a strong social network may buffer the deleterious impacts of household crowding.
- **Conclusion**: Targeting housing conditions and fostering social support as part of population health intervention might contribute to improving psychosocial health and well-being in Greenland.

Riva, M., Lytken Larsen, C.V., Bjerregaard, P. Social and geographic inequalities in blood pressure among Inuit in Greenland.

- **Background**: A burgeoning scientific literature demonstrates the salience of community conditions in the aetiology of cardiovascular diseases (CVD). This body of research has yet to be extended to examine health variation between Indigenous peoples and between Indigenous communities. This study examines individual-level risk factors and community-level conditions associated with elevated systolic (SBP) and diastolic (DBP) blood pressure (BP) among Greenlandic Inuit.

Methods: Data on 3108 Inuit aged 18 years and older are from the Inuit Health in Transition–Greenland Survey. Respondents lived in 22 communities characterized by their settlement type (towns vs. villages) and deprivation level. Association between blood pressure, community deprivation level and settlement type was assessed using multilevel analysis, adjusted for individuals' age, sex, marital status, socioeconomic position, use of hypertensive medication, and clinical and behavioural risk factors.

Results: Mean SBP was 130 mmHg, with 25% of participants having a SPB ≥ 140 mmHg. Mean DBP was 79mmHg, with 16% of participants having a DPB ≥ 90mmHg. There was significant variation in BP between communities, with about 2.5% of the total variance in SBP and 5% of the variance in DBP attributable to differences between communities. After adjustment for individual-level risk factors, SBP was significantly higher among people living in communities characterized by lower average equivalized household income. DBP was higher among participants living in more deprived communities and in villages (vs. towns). Inequalities in blood pressure were observed between participants' socioeconomic position, although results were less clear. Sex-stratified analyses further demonstrated the salience of community conditions in influence SBP levels among men.

Conclusion: Blood pressure was shown to vary significantly between communities in Greenland differentiated by socioeconomic conditions. This effect was independent of individual's socioeconomic and behavioural and clinical risk factors. Social inequalities in blood pressure were also observed, although results were less clear. Public health and social policies, programs and interventions targeting communities might yield population-wide health benefits.

Ruiz-Castell M, Laouan-Sidi EA, Déry S, Riva M. Individual and Community-level determinants of Obesity in Nunavik.

- **Objective**: This study examines the association between obesity and community-level sociocultural cohesion and individuals' psychosocial characteristics among Inuit adults of Nunavik.
- **Methods**: Cross-sectional data on 860 Inuit adults were collected from the 2004 Qanuippitaa? How are we? Nunavik Inuit Health Survey. Anthropometric data were used to create the variable obesity defined as a body mass index ≥30 kg/m^2. Information about individuals' perceived sense of community, social support, socioeconomic status and behavioral patterns was collected using questionnaires. Community sociocultural cohesion was measured using information from the 2006 Canadian census. Hierarchical Generalized Linear models were used to examine the association between perceived sense of community and community's sociocultural cohesion and obesity. Models were adjusted for age, sex, social support, socioeconomic characteristics, marital status, food security, smoking, diet and physical activity.
- **Results**: The prevalence of obesity was 25.9% among men and 31.4% among women. Risk of obesity was lower among people living in communities with higher sociocultural cohesion (OR: 0.46, 95 % CI: 0.34, 0.63) and perceived higher sense of community were protective to

obesity (OR: 0.41, 95% CI: 0.18, 0.95). These associations were independent of individuals' socioeconomic and behavioral characteristics.

- **Conclusion**: Despite a complex association between obesity and social determinants, results show the relevance of considering community-level sociocultural cohesion and individuals' psychosocial factors in the formulation of environmental programs of health promotion to reduce obesity in Nunavik.

Riva M., Ruiz Castell M., et al. Socioeconomic inequalities in the incidence of cardiovascular diseases among Inuit in Canada: Prospective analysis of the Nunavik Inuit Health Survey 2004-2011.

- **Background**: Compared to traditional behavioral and clinical risk factors associated with CVD, the role of social determinants on the incidence of CVD among the circumpolar Inuit has received less attention.
- **Objective**: To assess, prospectively, whether socioeconomic position (SEP) is associated with the incidence of CVD among Inuit living in Nunavik, Canada, independently of traditional risk factors.
- **Methods**: 908 Inuit adults participated to "Qanuippitaa? How are we?" Nunavik Inuit Health Survey. At baseline (2004), participants completed questionnaires concerning their health and socio-demographic characteristics and attended a clinical evaluation during which biological samples were collected. In 2011, participants' medical files were reviewed to assess the incidence of CVD since 2005. Incidence of CVD was treated as a dichotomous variable contrasting people with at least one diagnostic of CVD between 2005 and 2011. SEP at baseline was measured using information on income, education and employment. Association between SEP and incidence of CVD was measured using weighted logistic regression, controlling for baseline clinical (blood pressure, obesity, diabetes, cholesterol) and behavioral (smoking, diet, physical activity) risk factors.
- **Results**: Among participants, 8.5% were diagnosed with a CVD between 2005 and 2011. Lower SEP at baseline was significantly associated with the incidence of CVD, independently of clinical and behavioral risk factors.
- **Conclusion**: Beyond interventions aiming to change the more proximal (behavioral and clinical) risk factors of CVD, findings suggest that upstream efforts aiming to improve the socioeconomic and living conditions in the Canadian Arctic are likely to contribute to reducing the burden of CVD among the Inuit.

Related to objective 2. Prepare the 2016 follow-up of the Nunavik Inuit Health Survey

No results for the moment.

Related to Objective 3. Expand ongoing research on community and housing conditions in relation to Inuit health.

Refer to activities for objective 3 in the previous sections; data collection ongoing. No results for the moment.

DISCUSSION

Related to objective 1: Data analyses of the IICS

The harmonization of data from the three cohort studies to form the IICS allows for a range of

health-related issues to be investigated among the circumpolar Inuit.

Results of the study examining the association between self-rated health (SRH) and selected objective health indicators shows that few of the associations examined reached statistical significance, although there were differences between men and women. More in-depth analyses are needed to understand associations between SRH and other health measures with relevance for clinical practice and preventive strategies, and to assess the strength of SRH in predicting mortality among Inuit populations.

Results from the different studies examining the socio-environmental determinants of Inuit health, reveal the salience of housing and community conditions for health. For example, our study set in Greenland demonstrated that household crowding was associated with poorer mental well-being. Binge drinking was more common among people living in households without children. These effects were more important for women than for men. The association between household crowding and mental well-being was significantly mediated by social support. This suggests that having a strong social network may buffer the deleterious impacts of household crowding.

The two papers examining community conditions in relation to obesity in Nunavik and blood pressure in Greenland showed significant variations in the health outcomes between communities. Higher health risks were observed in communities characterized by poorer socioeconomic and cultural environment, independently of individual's socioeconomic and behavioural and clinical risk factors. Public health and social policies, programs and interventions targeting communities might yield population-wide health benefits in the circumpolar north.

Our study examining the predictive role of socioeconomic positions (SEP) measured in 2004 on the incidence of cardiovascular morbidity (measured for 2005-2011) showed that a lower SEP at baseline is significantly associated with increased risk of cardiovascular morbidity, independent of clinical and behavioral risk factors. These findings suggest that beyond interventions aiming to change the more proximal (behavioral and clinical) risk factors of CVD, findings suggest that upstream efforts aiming to improve the socioeconomic and living conditions in the Canadian Arctic are likely to contribute to reducing the burden of CVD among the Inuit.

Related to objectives 2 and 3

Nothing to report for the moment.

CONCLUSION

Related to objective 1: Data analyses of the IICS

The development of the data platform from harmonization across heterogeneous cohort studies, and the analysis of the rich health, socioeconomic and environmental information it contains, will facilitate knowledge to action and the development of regional and international policies to promote health.

Related to objectives 2 and 3

Nothing to report for the moment.

Overall conclusion/concluding thoughts on this project

I/We would like to acknowledge the immense contribution of Eric Dewailly to this project. Developing an International Inuit cohort study was his vision, one that was shared, but sometimes with less enthusiasm, by the PIs of the other cohorts. Over the years Eric has convinced his colleagues of the importance of bringing the data together to understand health and its determinants in the Arctic. We will continue his work in that regards. In 2015, we will finalize and officialise the process of accessing data from the IICS. We may, for the time being, focus our work on Nunavik and Greenland, with whom our working relations only grew stronger since Eric's passing.

Eric was a true mentor. He made available resources from this project (in terms of data and a bit of funding) to support the development of a new component to this project, one that focusses on the social and environmental determinants of health which Mylene Riva led. Early involvement in this project allowed her to publish scientific articles and rapidly develop a competitive research program. In 2013-2014, she submitted an application to a young investigator award to the Fonds de recherche du Québec – Santé, which was funded. She also submitted proposals to the Canadian Institutes of Health Research and ArcticNet Phase 4 to pursue her work on housing and health in the Arctic. Both were funded. In addition, she is the PI of the "community component" of the 2016 follow-up of the Nunavik Inuit Health Survey, which is in part funded by ArcticNet. These "activities, results, discussion and conclusion" don't fit within the overall scheme of the report. But we thought it was relevant for ArcticNet to know that beyond "tangible" results such as scientific publications, conferences presentations and the building of a database, the project International Inuit cohort study: developing the next phase also contributed to launching an academic career.

In addition, this project was also central to the PhD and postdoctoral work of several students, whose work was supported by scholarships from the Santé-CAP inter-university program in global health (Maria Ruiz Castell, postdoctoral fellow; Marie Baron, PhD student), Fonds de recherche du Québec – Santé (Beatriz Valera, postdoctoral fellowship), and Canadian Institutes of Health Research (Catherine Pirkle, postdoctoral fellow). All postdoctoral fellows are now occupying research (Ruiz Castell, Valera) or academic (Pirkle) positions in Québec City, Luxembourg, and Hawaii.

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IMPROVING ACCESS TO UNIVERSITY EDUCATION IN THE CANADIAN ARCTIC

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ABSTRACT

Increased participation in post-secondary education is of primary concern for Inuit. The goal of this project is to provide evidence-based research on Inuit participation in University education throughout Inuit Nunangat and to promote a national discussion amongst providers of university programs in Inuit Nunangat, Northern institutions and Inuit organizations in order to develop a more coordinated effort in program delivery, curriculum development. More specifically this research has three objectives: 1) Make an inventory and evaluation of past and present university initiatives in Inuit Nunangat or for Inuit in terms of curriculum, delivery methods and success, 2) Evaluate the Inuit Peoples needs and experiences with post-secondary programs or courses in order to better understand educational paths and university successes from the point of view of the Inuit 3) Develop different scenarios to improve access to university education for Inuit and Northerners in Inuit Nunangat. The data is being collected through surveys, in-depth interviews and workshops. This research provides evidence-based data on the Inuit students' university experience and Inuit participation in university programs. The definition of university and educative success from a point of view of Inuit will help university program providers deliver programs better adapted to the needs of Inuit students. The project aims to monitor Inuit student success according to this definition. The project will also inventory and evaluate the university program delivered in Inuit Nunangat and for Inuit students, and develop scenarios to improve access to university program for Inuit students.

KEY MESSAGES

The project has identified many key issues relating with Inuit post-secondary education:

- Post-secondary courses and programs have been offered across the North since the 1960s, most typically in reaction or response to economic pressures and opportunities that have arisen;
- Inuit post-secondary students are striving for more choices: choices in universities, programs and courses and choice in alternating work and school and thus studying at their own pace;
- Inuit students face a great deal of challenges when undertaking post-secondary education: in the North, there is a lack of housing and a lack of choice in post-secondary programs. In the South, students face loneliness, problems of adaptation, of funding, etc.;
- Funding opportunities are not similar in every Nunavut region for post-secondary students since some have access to funds from their Inuit organizations and not others. This has been confirmed by the data from the survey conducted amongst Nunavut Inuit with a postsecondary study;
- Women are more likely to be successful in school but are still behind men in terms of income and job position;
- Inuit speaking Inuktitut at home are more likely to be less successful in terms of education and job but a minority amongst this group is very successful in terms of job and income;
- Inuit with postsecondary education are likely to live, to work, or to want to go back in their community.

The Inuit students have identified the following solutions:

- In general: better funding programs and more equity between regions;
- In the North: better housing to allow to have its own space for studying, more choices in the type of program offered (not only programs geared toward the needs of the industry);
- In the South: student support in the southern universities, better guidance for choosing the programs, many student had no idea of what the program involved, coordination of student to avoid sending students alone in a program. Inuit students cohorts could be organized through a website with a list of student willing to take a program in the South;
- Participants stressed the importance of role model and mentorship;
- The cohort model increases the success of students because it creates a collaborative and mutually supportive community of learners who share experience and who faced many of the same challenges;
- Support (family, academic, professional, etc.) needs to be increased;
- Program coordinators and instructors with direct experience living, working and researching in Nunavut understand Inuit Qaujimajatuqangit and the challenges and curriculum issues in education and can adapt the instruction and content to reflect students' experiences.

OBJECTIVES

1. Make an inventory and evaluation of past and present university initiatives in Inuit Nunangat or for Inuit in terms of curriculum, delivery methods and success;
2. Evaluate the Inuit Peoples needs and experiences with post-secondary programs or courses in order to better understand educa-

tional paths and university successes from the point of view of the Inuit;

3. Develop different scenarios to improve access to university education for Inuit and Northerners in Inuit Nunangat.

INTRODUCTION

Given the multiple and interconnected challenges within the Arctic, the absence of an accessible university level post-secondary institution in Inuit Nunangat is disquieting. The mandate during the first years of the project has been to provide evidenced-based research on Inuit participation in university education in Canada and to promote a national discussion amongst provider of university program for the Inuit. While, since 1981, the Inuit population has made noticeable gains in enrolment and completion at the high school, College and trade level (ITK & Research and Analysis Directorate 2006), access to university is still very limited in spite of a series of initiatives lead by a variety of Southern universities. As a result, the numbers of Inuit who have completed a post-secondary degree remain quite low (from 1.6% in 1981 to 2.7% in 2006). Recently, the Government of Nunavut and Inuit Tapirriit Kanatami have adopted strategies to increase post-secondary success (Government of Nunavut, 2011; National Committee on Inuit Education, 2011).

This lack of progress can be explained by many interrelated factors:

- The absence of a university in the North. Canada is the only arctic country that does not have a university north of 60 (Poelzer, 2009);
- The quality of high school education in Inuit regions (Hicks, 2005); and
- The relevance of curriculum (Poelzer, 2009). Indeed, Inuit culture should be acknowledged in educational programs to dispel the colonial heritage left by the imposition of western education in the residential school (Berger, 2001; Hicks, 2005). For this reason, the adaptation of curriculum to Northern needs is a critical issue (Silta Associates, 2007).

Other factors like the lack of confidence encountered amongst some Inuit as a result of years of colonization have also had an impact on university success as defined in the South (Rodon, 2008).

A few southern universities have strived to provide access, through specialized programs and/or supports for Northern students, to degree studies at the post-secondary level. These initiatives have never been coordinated however, have proven expensive, and have therefore been difficult to sustain. Furthermore, they offer only specific fields of study (Education and Health, one program in Public Policy and another one in Law), are only available in limited locations (mostly in the main regional center), and are often not permanent because of their expense (funding constraints or fiscal budget) or instability of partnerships. In general, at the post-secondary level, transition programs to universities do not exist. Moreover, there is very little monitoring or research from all Inuit jurisdictions regarding success of Inuit at the post-secondary level (Inuit Tapiriit Kanatami, 2008).

This research project worked to bridge this knowledge gap by gathering evidenced-based data on Inuit participation in University education throughout Canada. In order to achieve this objective, two types of activities were undertaken and are summarized in this report.

First, the team endeavoured to trace the history of post-secondary education in Nunavut and Nunavik. These historical data were gathered by S.K. Dalseg for Nunavut and F. Lévesque for Nunavik. As a way of supplementing this information, inventories and evaluations of past and present university initiatives in Inuit Nunangat were also undertaken by K. Black and S. K. Dalseg.

Secondly, the needs and experiences of post-secondary Inuit students were assessed through surveys, interviews and workshops. This research were led by T. Rodon and, for the master of education program, by the UPEI research team.

Finally, the team was able, throughout the project, to foster a national discussion amongst stakeholders about the different scenarios to improve access to university education for Inuit and the creation of a northern university in Nunavut. This was made possible through the organisation of two workshops in 2011 and 2012 and of two sessions on Inuit education during the ArcticNet meetings in 2014 and through the organization of a meeting in Iqaluit in March 2015 to discuss with northern stakeholders the creation of an Inuit Nunangat University.

ACTIVITIES

1. History of post-secondary education

1.1. Institutional and Social History of Adult and Post-Secondary Education

During 2011-2013, Sheena Kennedy Dalseg conducted archival research in Ottawa, Yellowknife and Igloolik, and semi-structured interviews with key stakeholders, including former and current government employees, former adult educators, former students, and Inuit leaders. This work has enabled us to build comprehensive knowledge of the institutional social history of adult and post-secondary education in Inuit Nunangat, and its links to democratic community development. As a second step, between October and April 2014, Sheena Kennedy Dalseg met with twenty advisors to help us interpret our archival and historical findings.

A number of publications are planned or currently underway based on this research:

- In Fall 2014, Sheena Kennedy Dalseg submitted a paper entitled, "Creating Citizens, Building Societies: Adult Education as if Community Mattered", for publication in a special issue of the journal Historical Studies in Education. The article was accepted for publication and will be published in Spring/Summer 2015. The article traces the evolution of adult education programming in the Eastern Arctic, through three critical transitions between 1965 and the late 1980s. In particular, this paper explores the role that Frontier College played in the development of adult education programming in one Nunavut community, Igloolik, and its contribution to democratic and community development in the context of the Government of the Northwest Territories' (GNWT) larger political and economic objectives. Sheena Kennedy Dalseg presented an earlier version of this paper in October 2014 at the Inuit Studies Conference in Quebec City.
- Sheena Kennedy Dalseg is currently revising a conference paper on the Northwest Territories Legislative Special Committee on Education (1982), to incorporate interviews she conducted in March/April 2014 with members of the special committee. She will present this revised version of the paper at the June 2015 Canadian Political Science Association conference in Ottawa, ON. Following this, she plans to submit the paper to the journal Canadian Public Administration in Fall 2015. The Special Committee is often cited as an important moment in the history of education policy in the NWT and Nunavut but very little is written about it.

1.2. Creating Citizens, Building Societies: Schooling and Social Change in the Eastern Arctic

The rapid introduction of formal education in the 1960s brought massive changes to Inuit family relations and society. The complex Inuit experiences of these changes are not generally represented in writing about the period. Sheena Kennedy Dalseg's doctoral research seeks to document and understand the extent to which formal education, including adult and post-secondary education, influenced peoples' ideas about, and the ways in which they practiced, citizenship in Igloolik, NU. She will trace the evolution of the concept and practice of citizenship alongside the evolution of the education system between 1960, when formal schooling was introduced by the federal government, and 1999, when Nunavut was founded.

In March 2013, Sheena Kennedy Dalseg traveled to Igloolik to conduct preliminary archival research at the Igloolik Oral History Project, and community consultation for her dissertation work. In September 2013, Sheena Kennedy Dalseg defended her dissertation proposal and began her dissertation research.

Between October and April 2014, Sheena Kennedy Dalseg undertook archival research in Ottawa and Yellowknife, and conducted twenty interviews with key advisors. Between February and June 2014, she spent eight weeks in Igloolik conducting oral history interviews with 40 community members representing different generations and segments of the population. She worked closely with a community co-researcher, Francis Piugattuk. During these trips, she also completed interviews for the Adult Education paper, and also for the Special Committee on Education paper. These trips were partially funded by ArcticNet.

In the next months, Sheena Kennedy Dalseg will continue her dissertation research. She will travel to Igloolik in March 2015 to continue her community research, with a stop in Iqaluit to meet with representatives from the Department of Education, and to review available historical materials in Iqaluit. ArcticNet, NSTP and SSHRC will share funding for the trip.

1.3. History of post-secondary programs in Nunavik

This project consists of writing a history of non-traditional education in Nunavik from 1939 until now. During the 2013, research was aimed at finding information on the curriculum that was taught in federal day-schools from 1949, in provincial schools from 1963 and in schools managed by the Kativik School Board since 1978. A literature review gave little results, so the offices of the ministère de l'Éducation, du Loisir et du Sport of Quebec and its different regional departments were contacted, as well as archivists at the Departmental Library of the Corporate Information Management Directorate of Aboriginal Affairs and Northern Development Canada. In 2014, Maxime Mariage, master student at Laval University, was hired to collect information on education policies and their application, once again through a literature review. Francis Lévesque and her student Mylène Jubinville, continued the work by searching in the archives in Ottawa. Their preliminary results were presented at ArcticNet Scientific Meeting at Ottawa in December 2014. Their work will continue in 2015 with final results being published by the end of 2015.

2. Past and present university initiatives

2.1. Working Paper: Tracing the Idea of a Northern University

Originally written as a working paper in 2012, Tracing the Idea of a Northern University explores the history of proposals and initiatives to establish a university in the territorial North. Building upon foundational research by Amanda Graham (Graham, 1994; Graham, 2007; Stephens & al., 2008), and in the context of the 2010 initiative by the Walter and Duncan Gordon Foundation to advance the public discussion of the issue (see publications of the foundation online) the working paper traces the history of the various—often competing—visions for a northern university from 1960 to 1998, before Nunavut was founded. When we undertook this project, we saw it as an essential first step towards our larger project of drawing out key historical moments and actors, discussions, and debates surrounding adult and post-secondary higher education in the Northwest Territories (NWT) and Nunavut.

In 2014, Kelly Black submitted a paper drawing upon and extending some of the research and analysis in Tracing to The Northern Review, where it is under review.

In May 2014, Kelly Black presented some of the research growing out of the working paper at International Congress of Arctic Social Sciences (ICASS). A digital version of his presentation, An Institutional and Social History of Post-Secondary and Adult Education in the North is available online.

In addition, Kelly Black also developed a contemporary inventory of post-secondary programs offered in the North by southern universities, as well as an inventory of post-secondary transfer programs/credits available through the northern colleges. This work informed the Northern University Futures project.

2.2. Northern University Futures

The historical work on the idea of a northern university will be presented in two additional documents: the first, a discussion paper that brings together the contemporary (post-1999) discussions about developing a university in Northern Canada and offers some potential "next steps" for decision makers; and the second, a journal article concerning the potential role and impact of a northern university in Nunavut and the NWT that builds upon international research on the impact of universities in the political economy of developing regions. As a first step in developing the ideas for these projects, Kelly Black and Sheena Kennedy Dalseg drafted a working paper, entitled Northern University Futures in Fall 2014, which has three primary objectives: to document and draw together divergent contemporary conversations about establishing a university in the North; to situate the development of a university in the broader political economy and policy history of Northern Canada; and to identify key decision points and ideas for how to get started, including costing.

Sheena Kennedy Dalseg presented a version of this paper at the ArcticNet Arctic Change conference in Ottawa in December 2014 to an audience, which included Mary Simon, Nunavut Minister of Education Paul Quassa, the president of the Nunavut Arctic College, and faculty from the University of the Arctic. A digital version of Sheena Kennedy Dalseg's presentation is available online.

In the next month, the team researchers will focus on the continuation and completion of the writing projects:

- Black and Kennedy Dalseg's "Northern University Futures" discussion paper and journal article.
- Short briefing notes based on these projects will be developed and made available online for a general audience.
- Abele and Kennedy will complete a journal article submission on the potential role and impact of a northern university in Nunavut.
- As part of our commitment to make research results more accessible, we also plan to record members of the research team discussing Northern education policy, in historical perspective, to be published online in the form of podcasts in English and Inuktitut, available through IsumaTV. Other members of the "Improving Access" team have shared their results in this way. We also plan to devise a plan for future digital dissemination of our results, in English and Inuktitut.

3. Needs and experiences of post-secondary Inuit students

3.1. Monitoring educational and professional success amongst Inuit of Nunavut who have registered in a post-secondary program

In early 2011-2012, Thierry Rodon and Francis Lévesque developed a project called Monitoring educational and professional success amongst Inuit of Nunavut who have registered in a post-secondary program. The aim of this project was to measure and monitor the level of success enjoyed by Nunavut students who attend post-secondary education. ArcticNet funds the project through Thierry Rodon's project Improving Access to University Education in the Canadian Arctic. In March 2012, the project also got funds from the Nunavut General Monitoring Plan (NGMP).

After the preliminary results were presented to Nunavut stakeholders in 2013, stakeholders asked the team to pursue the project. Funds were again obtained from the NGMP. A total of 372 surveys were administrated in Nunavut communities and in Ottawa.

The final results were presented to the Nunavut stakeholders at the Nunavut Research institute in Iqaluit on February 4th, 2014. A report was recently published and distributed. Jean-Luc Ratel was hired in January to develop a cross-analysis of the quantitative data with the qualitative data that was collected in the first three years of the project. A complete analysis will be presented in Spring 2015.

3.2. UPEI Graduate Students

The UPEI research team has completed gathering and analyzing data related to the experiences of graduates of the Master of Education (MEd) Nunavut program offered between 2010-2013. The program finished in June 2013 and there are no plans to offer iterations in the near future. In 2013, the focus of the research has been on data analysis. In 2014-2015, dissemination of results and publications were the activities undertaken:

- Completion of an edited book of academic papers written by nine selected MEd graduates (from both the 2009 and 2013 graduating classes) will be widely advertised between February and June with publication in July, 2015 by Canadian Scholars' Press Incorporated/Women's Press.
- Contribution of MEd final paper abstracts to the publication of Northern Public Affairs (February 2014).
- Nunavut MEd 2013 graduates' final research papers were edited and formatted for dissemination in various forms.
- The team worked cooperatively with the UPEI Robertson Library's digital collection "Island Scholars" to create a dedicated online space for Nunavut Master of Education final research papers (Arnatsiaq, 2013; Cunningham, 2013; Etuangat, 2013; Flaherty, 2013; Iblauk, 2013; Iglookyouak, 2013; Kauki, 2013; Kusugak, 2013; Netser, 2013; Noah, 2013; Putilik, 2013; Tigullaraq, 2013; &Tootoo, 2013). Each student in the program was contacted, and signed permission forms to make their papers free and available in the public domain. Eight of the 13 papers have been uploaded to date.
- An electronic book (ebook) of Nunavut MEd student research papers is nearing completion will soon become available for download on the program website http://projects.upei.ca/nunavut/. This free ebook collects each paper and makes them available in one document, to serve as a legacy document. This ebook will represent the diversity of perspectives and research that came from students across Nunavut and Nunavik. The ebook will serve as a relic of what can be produced from a program even when students follow a course-based route.
- Completion of the Nunavut section of the UPEI website showcasing MEd 2013 graduates and their writing, as well as the research documentaries and youth focused research on high schools. (http://projects.upei.ca/nunavut/).
- The final report was presented to the Government of Nunavut on the Nunavut Master of Education program. It shared research findings on the delivery of one graduate–level program in Nunavut. Lessons can be learned from this program, and applied to other educational programs in Inuit Nunangat. A digital version of

the Nunavut MEd report will be uploaded onto a project website, and will be fully accessible to the public. http://projects.upei.ca/nunavut/final-report-2010-2013/.

- Sharing or research results of the Nunavut MEd program took place at: (i) an International conference focused on indigenous education (Wipc:E 2014 in June 2014 in Hawaii); (ii) at the 19th Inuit Studies Conference with a focus on Inuit knowledge (in October, 2014 at Laval University, QC); and (iii) at the International Arctic Change conference with a focus on research findings (in December, 2014 in Ottawa, ON).
- Sharing of research results in print: a co-authored article published in Northern Public Affairs (Walton & al., 2014); National dissemination of findings in a book featuring Nunavut MEd graduates' research (Walton & O'Leary, 2015); International dissemination of research in chapter in an international book, Education in North America (Mulcahy, Mulcahy & Saul, 2014), which refers to the Nunavut MEd program as an example of indigenous education in Canada.

Two additional students' papers will be uploaded onto the Island Scholar collection, and further research on copyright issues will take place to determine whether graduates whose papers will be published in Sivumut–Towards the Future Together: Inuit Women Educational Leaders in Nunavut and Nunavik can also be published in the ebook. Also, Jeela Palluq-Cloutier (2014) is now submitting her Master of Education thesis, Standardization of Inuktutut in the Educational System in Nunavut.

3.3. Tukitaarvik–Inuit Student Centre

Tukitaarvik is an interactive website providing information and networking for Inuit students interested in post-secondary education (www.tukitaarvik.ca). The website was officially launched in November 2013, at Nunavut Sivuniksavut (NS). Since then, it was presented at different occasions (Inuit education research Forum, Inuit Qaujisarvingat National Committee, the 9th National Inuit Youth Summit (NIYS) and the ArcticNet's 9th Annual Scientific Meeting (ASM 2013)), bookmarks were distributed by ITK to each high school across Inuit Nunangat and articles were published in different magazines (Above and Beyond, July 2013; Nipiit Magazine, Spring 2013, issue # 7; Inuktitut Magazine, Winter 2014, issue # 114). Interviews of Inuit students were also recorded for the website.

Until December 2014, the website was managed by the Youth Department at Inuit Tapiriit Kanatami (ITK) and, since January 2015, ITK co-manages the website with Laval University. Approximately two staff from ITK (Carrie Grable, Hayley Moorhouse) and two from ArcticNet (Teevi Mackay and Lucille Villaseñor-Caron) are directly involved in the project (excluding management, IT, and ITK communications staff), of which five were current students or recent graduates. Pam Gross, former student in the NGMP project and Teevi McKay have been hired to manage the website from Laval University. Currently, there are 168 Tukitaarvik members registered, near the double of the number reported last year (85).

4. Towards an Inuit Nunangat University

4.1. Education and University in Inuit Nunangat–ArcticNet Scientific Meeting 2014

Thierry Rodon co-chaired two sessions on Inuit education, December 9th, 2014, as part of the Arctic Change meetings. The first session, Education in Inuit Nunangat in a Time of Change, allowed researchers to present their work on education in Inuit Nunangat. Francis Lévesque presented his research on the history of education in Nunavik. The second session, Inuit Nunangat University: Issues and Prospects, gathered the experts Paul Quassa, Nunavut minister of Education; Mary Simon, chairperson of the National Committee on Inuit Education; Lars Kullerud, president of the Arctic University, and Keith Chaulk, director of the Labrador Institute of Memorial University, for a roundtable on Inuit Nunangat University. This session was the subject of an article in Nunatsiaq News.

Another meeting gathering stakeholders will be held in March 2015 in Iqaluit in order to develop a plan for the establishment of an Inuit Nunangat university. Kelly Black and Sheena Kennedy Dalseg will be co-authoring a background paper for the workshop with Thierry Rodon, and Sheena will develop a report on this workshop. The report will be summarized and will appear in a special online feature of Northern Public Affairs.

4.2. Northern Public Affairs Special Issue on Inuit Education

In partnership with the Amaujaq National Centre for Inuit Education, Northern Public Affairs (led by Sheena Kennedy Dalseg) published a Special Issue on Inuit Education, published in April 2014. The "Improving Access" team contributed an article to the issue, and Sheena Kennedy Dalseg wrote the editorial.

RESULTS

1. History of post-secondary education

1.1. Institutional and Social History of Adult and Post-Secondary Education

The history of adult and post-secondary education in Inuit Nunangat is intertwined with federal and provincial development dreams and actions, shaped and reshaped by Inuit parents' and students' choices, and initiatives of a few non-governmental organizations devoted to democratic development. The complex and dynamic relationship among these forces has created the education and training situation that exists today, defining opportunities and limiting them as well.

Hundreds of adult education and post-secondary courses and programs have been offered across the North since the 1960s, most typically in reaction or response to economic pressures and opportunities that have arisen. These programs can be divided into three main categories: academic, vocational/technical; and cultural-linguistic programs.

The vast majority of programs and courses were designed and provided by government either through the network of Arctic College community learning centres, or directly by government departments for labour force training purposes. Other providers include non-profit organizations, like Frontier College, Nunavut Sivuniksavut or the Piqqusilirivvik Cultural School, and industry associations, such as those providing training for oil and gas industry employment.

In the absence of a university in the North, there exists a strong tradition in the Arctic College to establish institutional partnerships with southern universities to offer degree programs. The longest-standing program of this nature is the Northern Teacher Education Program (NTEP).

In the years between the mid 1960s and the mid 1980s, adult education underwent three significant transitions involving both administrative and philosophical components: the first in 1966 following the introduction of the Home Management Education Program; the second following the transfer of responsibility for education from the federal to the territorial government in Yellowknife in 1970; and the third arising after the Special Committee on Education report in 1982 and the resulting creation of the Arctic College.

The first transition saw a gradual shift from ad-hoc adult education, which characterized the period leading up to roughly 1965 when the federal government introduced the Home Management Education Program. The home management education program was tied to the housing program intended to draw Inuit off the land into settlements; and was motivated by the federal government's overarching welfare-state policies and its belief that it knew what was best for the Indigenous peoples living across Northern Canada. The Home Management Education Program was staffed by both Inuit and non-Inuit and it's relative success signalled that further civic-based adult education programming might be needed and wanted in the rapidly growing settlements.

The second transition took place after the GNWT took over responsibility for education in the East in 1970. In 1971, the GNWT contracted Frontier College, Canada's oldest literacy organization to help develop an adult education program for the territories. At the time, Frontier College was itself going through an important transition. It was experimenting with "community adult education", which involved sending full-time dedicated adult educators into communities that were experiencing periods of social or economic transformation, as opposed to the "labourer-teachers" it usually employed. Only a handful of communities were staffed through the Frontier College contract (Igloolik was one of them), but many of the people who came North during the 1970s to be adult educators had previously worked for Frontier College, and carried its philosophies with them.

During this period, adult education went beyond academic courses like basic upgrading. The community adult education centers were established, including local libraries; radio societies and community newspapers; local committees (education, housing, elders', youth, etc). Although adult educators were technically agents of the state, many adult educators saw themselves as "animators", whose role it was to support the learning and development priorities of community members. One participant I spoke with said that part of their role was to help people learn how to "manipulate the system". The local institutions, which were developing during this period, engaged community members and generated momentum and opportunities for local leadership, innovation, and entrepreneurship. This generation of adult educators, both Inuit and Qallunaat, tended to align themselves with the movement toward Inuit self-determination and worked to support this at the community-level by creating space for grass roots rather than top-down development.

The third transition came after the 1982 final report of the Special Committee on Education. The SCOE had 11 recommendations pertaining to adult and post-secondary education, including the establishment of a college system across the NWT. The *Arctic College Act* was passed in 1986. The GNWT was now in the process of developing its own adult education system and rather quickly following the passing of the *Arctic College Act*, the Frontier College contracts were terminated and the approach to adult education began to change. The institutionalization of adult education in the GNWT brought more resources, and more supports for educators, including more professional development opportunities; on the other hand, it also meant that educators who had previously had more independence from the government were expected to answer to the government rather than the community. The accountability structures shifted and adult education programming and priorities started to be determined by the Department of Education and the College, rather than at the community level. There was resistance in Igloolik to these changes.

Over time, adult and post-secondary education has also become increasingly focused on improving the employability of Inuit in the wage economy labour force (in both the private and public sectors). This dynamic has played out differently in the four territories of Inuit Nunangat.

1.2. History of post-secondary programs in Nunavik

Very little information on the curriculum taught in residential school, be they provincial or federal, was found. Available documents focus mainly on the issues of language. However, information is more readily available for the content of courses taught in Arctic Quebec, since the Inuit have started to assume responsibility for elementary, secondary and adult education in 1975. If Kindergarten, Grade 1 and 2 only are taught in Inuktitut, the other grades are taught in English or French. The curriculum follows the ministère de l'Éducation, du Loisir et du Sport of Quebec guidelines while incorporating Northern content, such as Inuktituk classes. In the upcoming month, research will continue in order to provide more evidence.

2. Past and present university initiatives

2.1. Tracing the Idea of a Northern University

Some of the results that emerged from Tracing the Idea of a Northern University include:

- Competing visions for a northern university are directly linked with competing visions of the future of the Canadian North.
- Discussion and debate surrounding post-secondary education has evolved alongside the process of Indigenous self-determination, particularly in the Eastern Arctic. These efforts culminated in the 1982 Learning: Tradition and Change report and 2011's National Strategy on Inuit Education.
- Local and regional cultural differences, as well as the need for economic benefits, have been points of contention in determining curriculum, campus locations, and governance.
- The most prominent conceptualizations of a northern university were set on implementing a southern model that would facilitate research projects originating in southern universities.
- There is a need for research on the potential economic as well as social impact of the establishment of a northern university, along with a discussion of different models.
- A strong and distinctive theme in Nunavut and the NWT is the search for a university system that would embody Indigenous cultures' approaches to education. Non-governmental groups in each territory have advocated for this, and in the NWT, a distinctive model has been implemented (Dechinta Knowledge and Learning Centre).

3. Needs and experiences of post-secondary Inuit students

3.1. Educational and professional success amongst Inuit of Nunavut with post-secondary experience

3.1.1 Descriptive analysis

Between 2012 and 2013, 372 surveys were conducted with current and past Inuit post-secondary students from Nunavut. Among the respondents, most were women. They were aged between 18 and 64 years old and were speaking Inuit languages or English or both. All respondents had post-secondary experience and most of then were employed and satisfied of their job. The survey shows that Inuit with post-secondary education are likely to live (65%), to work (53%), or to want to go work in their community (67%). Finally, the data also shows that respondents living in their home community are more likely to be employed and to earn a higher income.

3.1.2. Correlations

One of the main objectives of this project was to study the relationship between educational success and job satisfaction. Three variables influence this relationship: gender, language, and region. The following section reminds us the results from the preliminary analysis. As Jean-Luc Ratel has been hired to develop a cross-analysis of the quantitative data with the qualitative data that was collected in the first 3 years of the project, a complete statistical analysis will be available in Spring 2015.

- **Gender**: Inuit women have a higher school attainment than men. They have completed high school at a higher rate and are more satisfied with their education. There is also a strong correlation between gender and job status. However, post-secondary education did improve the job situation of most people who, in majority, found better jobs after their post-secondary education than before. However, there are notable differences between men and women. Although post-secondary

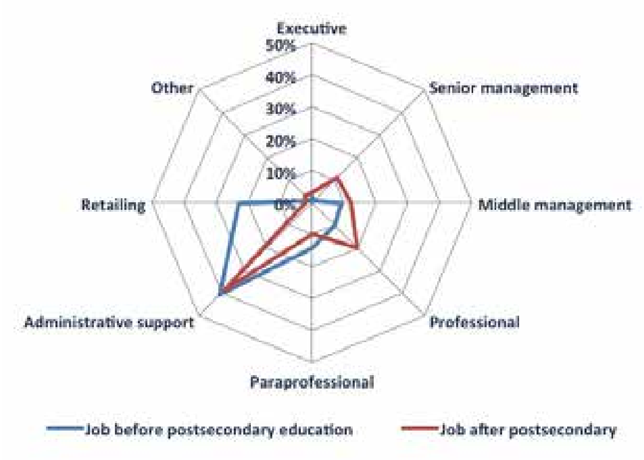

Figure 1. Job status before and after post secondary education, among women.

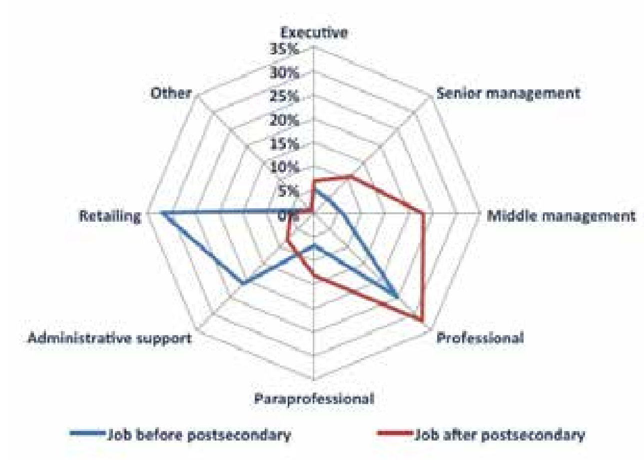

Figure 2. Job status before and after post secondary education, among men.

education gives access to better jobs to both men and women, men tend to obtain better jobs after their post-secondary education (Figures 1 and 2).

- **Language**: Inuit who speak English at home are more likely to graduate from high school. Language also affects job situation and job satisfaction. Data shows that people who speak English at home are more likely to have full-time jobs than people who speak an Inuit language at home (Figure 3).
- **Funding**: In order to pay for their education, most Inuit students received a loan and/or a grant. However, access to funds is different from one region to another. While every Nunavut student has access to the Financial Assistance for Nunavut Students (FANS), some have access to grants from regional Inuit organizations offering, and not others. To understand why this is the case, an analysis of funding programs available to Nunavut Inuit must be undertaken (Figure 4).

3.2. Nunavut MEd Graduate Students

The Nunavut MEd demonstrated that a graduate program in education could be successfully delivered in one of the regions of Inuit Nunangat. The MEd program was based on a vision and plan cooperatively developed between the Faculty of Education at the University of Prince Edward Island and the Department of Education, Government of Nunavut that guided two iterations of the program from 2009-2013. The success experienced in the Nunavut MEd was based on the partnership with the Department of Education, Government of Nunavut that provided adequate funding to provide both Inuit and university based instructors, access to counselling support and organizational and logistical supports that enabled students to travel from their communities to central locations to complete courses.

Students participating in the MEd program were able to focus on their studies in intensive face-to-face courses, offered in a central location in Nunavut and for one summer on campus at UPEI, a distance education component was usually offered before a course started so that some of the readings and on-line discussion were completed before students travelled. All students participating in the MEd program had completed the Bachelor of Education (BEd) program offered by the Nunavut Teacher Education Program (NTEP) and certified by McGill University, providing them with some of the skills required to succeed in graduate courses; however, additional support, particularly with academic writing, was provided to most students.

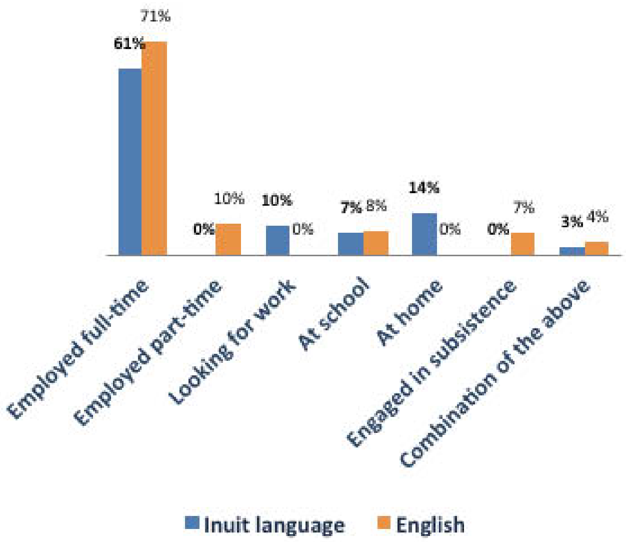

Figure 3. Current work situation by language spoken at home.

The cohort model brought together a group of qualified Inuit to complete ten graduate courses together which built a mutually supportive learning community that offered encouragement and raised motivation promoting successful completion of the program.

Graduates were motivated to complete the MEd because they believed it was important to act as role models in their communities and believed this would impact the future of education in Nunavut. Inuit and most university-based instructors in the MEd had previous and long-term experience teaching, leading, and working in education in Nunavut and were able to ensure that the courses were delivered in both Inuktitut and English with a focus on issues and priorities related to Nunavut.

The involvement of Elders in almost all the face-to-face courses was deeply valued by the students providing grounding in Inuit history and culture that they believed to very important. Thirty-seven Inuit educators now hold MEd degrees in Nunavut which raises educational levels significantly, impacting the quality of education offered in schools and providing Inuit with qualifications and confidence to apply for

Figure 4. Source of funding by region.

and be successful in a variety of leadership programs; however, in order for Inuit to succeed on a long-term basis, ongoing professional learning experiences and mentorship would be helpful.

Maintaining the community of emerging researchers and Inuit scholars who completed the MEd would be very valuable and providing ongoing mentoring to develop skilled research leaders would be important.

Findings from research on the Nunavut MEd also indicated that graduates valued critical thinking skills, development of voice, and growth in leadership abilities. Graduates also experienced many important non-academic outcomes, including improved confidence, personal growth, healing, and decolonization.

Results also indicated that the Nunavut MEd program opened a door to graduate education that would have otherwise been unattainable to educators who were firmly tethered to home communities through family and employment responsibilities. Research revealed the benefits and importance of supporting Inuit educators to complete graduate studies in the North with colleagues. Given the implementation of the National Strategy on Inuit Education, ongoing legislative and policy changes in Nunavut, and the recent financial contribution to create a university in the Territory, skilled Inuit researchers and leaders are required in order to provide a sustainable future for the Territory.

DISCUSSION

Ever since it started, the project Improving Access to University in the Canadian Arctic and the various subprojects led by project leader Thierry Rodon and network investigators Fiona Walton, Frances Abele and Frédéric Laugrand have highlighted a certain number of preoccupations and knowledge gaps concerning post-secondary education in the Canadian Arctic. For example, the recording of undergraduate and graduate Inuit students' post-secondary experiences during project surveys, workshops (Ottawa-2010, Inuvik-2010, Kuujjuaq-2011) and focus groups highlighted many students' preoccupations but also allowed them to highlight some solutions they envision to improve post-secondary education for their peers. The comprehensive history of post-secondary education and the northern university concept within the NWT and Nunavut has showed how post-secondary and vocational programs are directly linked with competing visions of the future of the Canadian North and how they are not well adapted to Northern realities. The project also highlighted the lack of existing knowledge about the role of post-secondary institutions in the transmission of traditional knowledge from elders to children. Finally, the project has shown how support is crucial to increase the success of Inuit post-secondary students, even those with prior post-secondary experience. In 2014-2015, the research team set to disseminate the research results and translate them into concrete actions while also starting to fill some research gaps by continuing already existing sub-projects and beginning new ones.

1. Institutional and Social History of Adult and Post-Secondary Education

The project Institutional and Social History of Adult and Post-Secondary Education found that the history of adult and post-secondary education in Inuit Nunangat is intertwined with federal and territorial development dreams and actions, shaped and reshaped by Inuit parents' and students' choices, and initiatives of a few non-governmental organizations devoted to democratic development. The complex and dynamic relationship among these forces has created the education and training situation that exists today, defining opportunities and limiting them as well. The history of adult education is a valuable lens through which to understand the changes over time to northern development policies and approaches. The literature on the history of adult education is limited; there is an urgent need for research by Inuit on the history of community-based adult education given the role that adult education played in the development of the settlements across the NWT and Nunavut.

This project also showed the necessity of studying the history of adult and post-secondary education programs in the other regions of Inuit Nunangat as well. Each region and indeed each community has its own story.

2. Tracing the Idea of a Northern University

If the project Improving Access to University in the Canadian Arctic established that there was a need for a University in the Canadian North (Rodon & al. 2011; Rodon & al. 2012, Rodon & al. 2015), the subproject Tracing the idea of a Northern University found that there was a need for research on the potential economic as well as social impact of the establishment of a northern university, along with a discussion of different models. A strong and distinctive theme in Nunavut and the NWT is the search for a university system that would embody Indigenous cultures' approaches to education. Non-governmental groups in each territory have advocated for this, and in the NWT, a distinctive model has been implemented (Dechinta Knowledge and Learning Centre). We hope that our continuing work on the political economy of developing a university in the Canadian Arctic will support the ongoing discussions by key stakeholders on what such an institution might look like.

3. Monitoring educational and professional success amongst Inuit of Nunavut who have registered in a post-secondary program

Although the analysis of the 375 surveys of Inuit with post-secondary education has not yet been entirely completed, the findings we have so far have allowed us to uncover some important patterns that should be further studied and addressed by public policy:

a. Women are more successful at the academic level and are more likely to further their education, however men tend to have better job (position and income). This pattern is also observed in the South but we need to explore further this in Nunavut since different cultural and social patterns may be at work.

b. Language is also a discriminating factor both in academic achievement and in the workplace. People who speak Inuktitut at home are more likely to have lower academic achievement, to feel not qualified for their job, to be unemployed and to have a lower income. However, looking closely at the data indicates that a minority of Inuktitut speakers are as successful as unilingual English speakers. It remains, that as a group, Inuit speaking English at home are more likely to be successful than Inuit speaking Inuktitut at home.

c. Funding issues have been often discussed during the workshops and focus groups conducted in the first two years of the project. In the survey, most respondents consider that the funding was not adequate, but the data indicates also a strong regional differentiation. People in the Kivalliq region are more likely to receive funding from Inuit organisation and less likely to receive it from Financial Assistance for Nunavut Students (FANS). The relation is reversed in Kitikmeot where you are more likely to receive funds from FANS and less from Inuit organisations. This issue was mentioned during focus groups and we need to explore the different funding programs to understand this difference.

d. Inuit with postsecondary education are likely to live, to work, or to want to go back in their community. This is clearly a very different pattern than what is occurring with non-Inuit students.

4. Nunavut MEd Graduate Students

Offering a graduate program in Nunavut would not have been possible without the supports provided by the Department of Education. The logistical challenges related to bringing up to 28 students together from across Nunavut and providing them with accommodation, per-diem costs and access to suitable classroom space would have been difficult to organize without a partnership committed to a shared vision for the program.

The success of the program is directly related to the ability to provide bilingual/bicultural courses with both Inuit and university-based instructors who have direct experience working in Nunavut. Courses in the UPEI MEd program at UPEI were maintained, but the content focused on Inuit education and the readings, as much as is possible, focused on topics related to educational leadership in Inuit communities.

Providing learning experiences that were decolonizing also proved to be enlightening and inspiring for the students. The first course, Leadership in Postcolonial Education, introduced a seminal text written by Māori scholar, Linda Tuhawai Smith, and started a dialogue related to the impact of colonization on education and efforts to decolonize the educational system in Nunavut. Students found the focus on decolonization to be very helpful and many of them used it as a theoretical and methodological lens in their final research papers (Wheatley & Walton, 2014).

The Nunavut MEd was designed specifically to be accessible to Inuit students in Nunavut. It was based on extensive survey research conducted in Nunavut in 1994 (Nunavut Boards of Education, 1995) and is informed by the Hunger for Professional Learning in Nunavut Schools, a doctoral dissertation completed by Fiona Walton (1998). Accessibility was facilitated by delivering most of the courses in Nunavut and bringing students together in a central location for intensive courses. Continuing to offer opportunities for Inuit students to dedicate significant time and effort to complete their graduate degrees will continue to positively impact Inuit society address the need to have highly educated leaders who can make decisions that will benefit Nunavut.

Maintaining the capacity building of Inuit educational researchers is a high priority for Nunavut. Education in Nunavut continues to face a crisis with issues related to bilingual education, student achievement issues at the high school levels that continue affect the graduation rates and many challenges related to addressing the special needs of Inuit students. The completion of a course-based MEd program provides the basic skills required to become a researcher, but it does not enable the graduates to lead and manage research projects. Building on and further developing research skills, particularly related to proposal and report writing, the development of ethical submissions, and the management and completion of research projects would be a valuable.

5. Tukitaarvik–Inuit Student Centre

One of the results of Improving Access to University in the Canadian Arctic was the realization that Inuit students needed more knowledge about programs, funding opportunities, other Inuit experiences of post-secondary education, etc. To facilitate the sharing of knowledge and networking among Inuit post-secondary students, it was decided to create a website that would offer 1) practical information to Inuit students, 2) advices and inspiration about post-secondary experience, and 3) networking function, providing students with an opportunity to learn directly from their peers as they explore viable career options. The website offers prospective students important information about programs and funding occasions, allows them to network together, and offers advices from former and current students. More importantly, the content of the website has been developed by Inuit post-secondary students for Inuit post-secondary students. Although it is still early to measure the impact this website will have, it is hoped that it will become one of the tools that will help increase access (and success) of Inuit post-secondary students.

CONCLUSION

Education is a priority of many Inuit leaders. The National Strategy on Inuit Education was made public in 2011 with the idea to graduate children confident in Inuit language and culture and capable of contributing to the emerging opportunities in Canada. In 2013, Inuit Tapiriit Kanatami launched the Amaujaq National centre for Inuit Education to implement the recommendations from the National Strategy. In that context, research on education in Inuit Nunangat is extremely important.

The knowledge generated by Improving Access to University in the Canadian Arctic' research teams has identified several key issues regarding Inuit post-secondary education. During this research project, the team was able to trace the history of post-secondary education programs in Inuit Nunangat and the history of university initiatives. Furthermore, through surveys, interviews and workshop, the team was able to evaluate the Inuit needs and experiences with post-secondary education. All of these results have been published and shared with Inuit decision-makers and the data were used, amongst other things, to create Tukitaarvik, which is now an integral part of Amaujaq's strategy on Inuit education. This website was established to respond to Inuit students concerns mentioned during the project's first focus groups. Knowledge has also been essential to stimulate a discussion on the different scenarios to improve access to university education and the establishment of a university in northern Canada. With the organisation of two sessions on Inuit education during the ArcticNet meetings, the team was able to present its finding on Inuit post-secondary education to experts working in education and Northern decision-makers. It fostered discussions about the need of a University in Inuit Nunangat and, following that session, another meeting is being organized for March 2015 in Iqaluit in order to develop a plan for the establishment of an Inuit Nunangat university. Thus, this research project has not only created meaningful knowledge on Inuit post-secondary education, it has played a key role

in the creation of educational structures to improve university education in Inuit Nunangat.

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ADAPTATION IN A CHANGING ARCTIC: ECOSYSTEM SERVICES, COMMUNITIES AND POLICY

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ABSTRACT

This project documents the changing physical, biological and socio-economic conditions that are affecting people in the Arctic and identifies policies and strategies to assist communities in dealing with these changes. The project builds on previous work on the vulnerabilities of Arctic communities, and it is feasible because of established collaborations with northern people and organizations. The project includes case studies in all four of the ArcticNet IRIS regions. One main focus of the project involves integrating scientific and traditional knowledge of ice, permafrost, coastal dynamics and wildlife with information about community use of these ecosystem services. The other main thrust is to identify the opportunities in existing policies and co-management arrangements for adaptation strategies to help communities deal with changing conditions.

KEY MESSAGES

- Current knowledge of vulnerabilities to climate change could form the basis for advancing the adaptation research agenda, from analyses currently weighted heavily toward problem identification and description to the development and implementation of practical adaptation initiatives.
- Adaptations to climate are unlikely to be undertaken for climate change alone but are more likely to be a response to problematic conditions that already exist in the community.
- Supporting efforts that increase financial, health, educational, and cultural capacity in communities will inadvertently enhance the adaptive capacity of the community to deal with current and future climate change risks.
- Consistent with the above, mine and other resource developments can augment the adaptive capacity of individuals and their families, as evident in the case of the Hamlet of Baker Lake's experience with the Meadowbank Mine. Such development can also augment collective capacities in cases where a development prompts efforts by Aboriginal governments to exercise their rights and interests, as evident in the case of the Labrador Inuit's experience with the Voisey's Bay Project. Where efforts are stymied by institutional arrangements, as is the case with the Hamlet of Baker Lake's attempts to manage well-being impacts associated with the Meadowbank Mine, disempowerment can lead to reduced collective capacity to manage current and future climate risks.
- Efforts to develop systems to monitor community well-being in light of mine development, as completed with the Hamlet of Baker Lake and Naskapi Nation of Kawawachikamach, provide an effective means of empowering communities to see and manage the impacts of resource development. This can serve to empower communities and thereby augment their collective capacity to manage current and future climate risks.
- Realizing adaptive capacity and overcoming adaptation barriers in Inuit communities requires policy intervention to: (1) support the teaching and transmission of environmental knowledge and land skills, (2) improve access to, and understanding of climate, weather and sea-ice information, (3) review and enhance search and rescue capabilities, (4) strengthen harvester support programs, (5) ensure the flexibility of fish and wildlife management regimes, (6) improve the ability of Inuit food systems to meet present dietary and nutritional requirements, (7) protect key infrastructure, and (8) review building codes and land-use plans in light of current and expected climate change.
- Inuit traditional ecological knowledge (TEK) underpins competency in subsistence and adaptations to changing climatic conditions through enhanced flexibility, hazard avoidance, and emergency preparedness.
- Food insecurity may be a consequence of changing demographic and economic conditions in the settlement that encourage women to set up households independently of men.
- Findings of food insecurity in arctic settlements may be interpreted as a response to the fear of cultural loss as it is to nutritional deprivation.
- Limited cold storage space for country foods contributes to periods of food insecurity for families in communities that do not have a community freezer. Support for community freezers enhances the adaptive capacity of households to shortages in country foods throughout the year.
- Hunters are coping with changes in the availability of some species of wildlife important for subsistence by taking advantage of the availability of new species, e.g. beluga whales in Ulukhaktok. This short term coping

mechanism has the potential to be maladaptive if the availability of beluga whales is a short-term phenomena and hunters divert investment in whale hunting equipment (e.g. boats) rather than other hunting equipment (e.g. snowmobiles, ATVs).

- Southern educators perceived learning success as individual means of accomplishment, including learning literacy skills, working towards a personal objective or building a career. Inuit on the other hand perceived learning success as collective, or contributing to the common good. As such, current methods for evaluating Inuit student success, individual standardized testing, are in conflict with Inuit perceptions of learning success.
- Inuit engage in a variety of risk management strategies to minimize the potential risks of sea-ice travel in an increasingly uncertain and hazardous environment. Sea ice represents a significant resource for health and protecting safe access to and navigation of this environment is crucial for health and wellbeing. With increasingly unpredictable weather systems and unstable ice conditions being associated with search and rescue events, the development of a system of safe shelters or refuges is one example of how communities are adapting to changing environmental circumstances.

OBJECTIVES

1. To integrate natural and social science and Inuit Traditional Knowledge in vulnerability assessments.
2. To examine the institutional structures and processes which facilitate or constrain adaptation to changing conditions in Arctic communities.
3. To engage northern communities in assessments of adaptation strategies and options.

INTRODUCTION

The Canadian Arctic is widely regarded as a global hotspot of climate change impacts (IPCC 2014). 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 particular sensitivities to the rapidly changing climate (Pearce et al. 2010). Climate models indicate continued and accelerated climate change in the foreseeable future, with further affects on Inuit livelihoods (Holland et al. 2010).

The main response of governments to concerns over climate change has been to seek reductions in greenhouse gas emissions to mitigate changes to the climate system. However, it is recognized that even with the most aggressive control measures, current greenhouse gas emissions commit the Earth to some degree of climate change requiring nations, regions, communities and individuals to undergo some level of adaptation (IPCC 2014). Adaptation in the context of human dimensions of climate change refers to an adjustment in human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (Smit and Wandel 2006).

Past research on climate change impacts and adaptations has often focused on modeling hypothetical adaptations in response to specific future climate change scenarios. Referred to as the 'impact-based approach,' these studies have been conducted at large scales, and focused on long-term changes in average climate conditions (variables most readily available from climate models) for the purpose of quantifying the net impact of climate change. Adaptation, if addressed at all, focused on implementing hypothetical technical measures. The impact-based approach has improved our understanding of the potential severity of future climate change impacts, but has not explicitly addressed adaptation processes. Recognizing this deficiency in knowledge and understanding of adaptation, recent adaptation research has drawn on theory from social vulnerability (e.g. Adger 2003) and works in human ecology of natural hazards and risk management (e.g. Cutter 1996) to develop an integrated understanding of vulnerability.

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? In the climate change field, the term vulnerability refers to the susceptibility of a system (community) to harm relative to a climate stimulus or stimuli, and relates to the exposure-sensitivity of the community to a climate stimulus and the capacity to adapt (Smit and Wandel 2006). Assessing vulnerability 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.

Project 1.1 Adaptation in a Changing Arctic: Ecosystem Services, Communities and Policy, worked with people in communities to examine human responses to climate change and identify opportunities to support adaptation. Project research conducted between 2014-2015 focused on gaining a better understanding of Inuit food security under changing climate and societal conditions, and the roles that non-climatic drivers of adaptation including education, health and Traditional Ecological Knowledge, play in driving adaptation processes. The findings from this research aim to provide information to support practical, community-driven adaptation initiatives.

ACTIVITIES

Ulukhaktok, NWT Research Activities [T.Pearce]

Time frame and study area: Field work involved spending long periods of time living in communities, studying at first hand what people do and say in particular contexts. Researchers spent between 3-4 months living in communities at times throughout the year. Data was collected through participant observation in relevant settings, semi-structured interviews using open-ended questions designed to understand people's perspectives, and analysis of relevant secondary sources of information–reports, publications, unpublished data. The study area included the community of Ulukhaktok and hunting areas on Victoria Island (Figure 1).

Research: Fieldwork focused on collecting data related to community adaptation to changes in climate and society. The following investigations were undertaken:

- examination of how policy interventions can help Inuit communities adapt to climate change [Dr. Tristan Pearce].
- examination of the role of Inuit Traditional Ecological Knowledge in adaptation to climate change impacts in the subsistence hunting sector [Dr. Tristan Pearce].
- analysis of data on food sharing activities among Inuit households [Dr. Tristan Pearce].
- collection of data on the vulnerability of an Inuit food system to climate and socio-economic changes and adaptation options [MSc Candidate Colleen Parker].
- collection of data on Inuit women's conceptualizations of and approaches to health in the context of adaptation to the health effects of climate change [MA Candidate Linnaea Jasiuk].

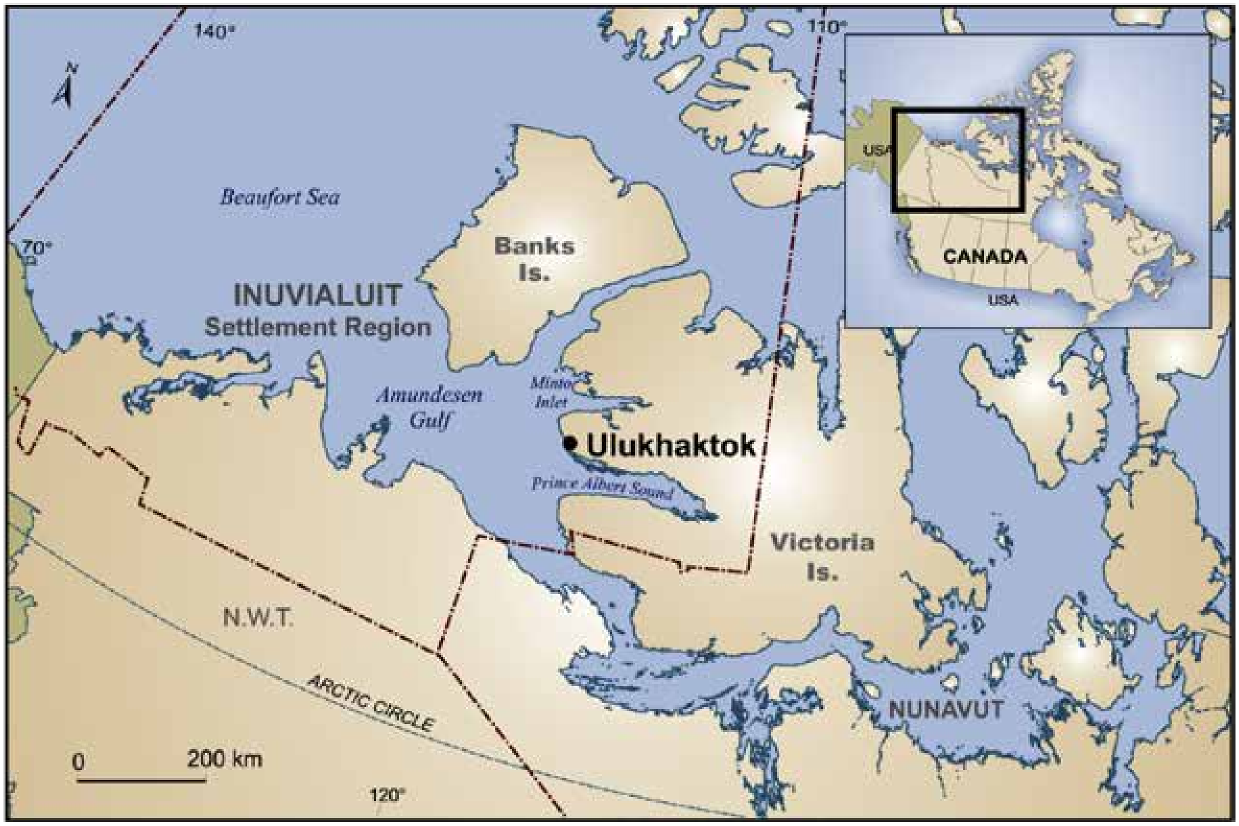

Figure 1. Map of showing the location of the Inuvialuit Settlement Region (ISR) and Ulukhaktok in the Northwest Territories, Canada

- collection and analysis of data on Inuit and southern educators perceptions of learning success [BSc Honours Genevieve Lalonde].

Baker Lake, NU; Naskapi Nation of Kawawachikamach; Taku River Tlingit (Atlin, BC) [B. Bradshaw]

- Dissemination of results from research with the Hamlet of Baker Lake, NU on community well-being impacts and benefits from mining were presented at the International Congress of Arctic Social Sciences (ICASS) in Prince George, B.C. (May 2014 [Zoe Barrett-Wood].
- Consultation visit with members of the Naskapi Nation of Kawawachikamach (spring 2014) to discuss working together to develop a system to monitor community well-being in light of possible mine development [Dr. Ben Bradshaw].
- Data collection with Taku River Tlingit, Atlin, B.C. (August/September 2014) and the Nunatsiavut Government, Nain (October/November 2014) to document their approaches to exercising their rights and interests around mine development. Data collection techniques included document review, key informant interviews, and participant observation [Dr. Ben Bradshaw; MA Candidate Caitlin Kenny].

Nain, Nunatsiavut Research Activities [C. Furgal]

- Completion of analysis and preparation of manuscripts for submission to journals.
- Revisions and resubmissions of manuscripts for publication.
- Presentation of results to Indigenous Health Conference, Toronto, ON.
- Discussion with Nain Ground Search and Rescue about development of safety shelters on the land to address issues of weather and ice being key factors in SAR events as identified in this project.

RESULTS & DISCUSSION

Community-Wellbeing Impacts and Benefits from Mining

Previous ArcticNet research in Baker Lake, NU, showed how mine and other resource developments can augment the adaptive capacity of individuals and their families, but can detract from collective adaptive capacity if communities are disempowered through institutional structures. New research completed with the Taku River Tlingit First Nation and Nunatsiavut Government has shown how collective adaptive capacity can be enhanced where efforts are made to develop new institutional structures in the face of possible mine development, which serve to empower communities.

There is growing interest among Indigenous communities experiencing mine and other resource developments to better track and manage community well-being. Previous efforts have relied on standard socio-economic indicators that fail to reflect Indigenous community priorities and values. Through a partnership with the Naskapi Nation of Kawawachikamach, a process for developing community-relevant indicators of wellbeing was developed, which established a baseline of community conditions against which change can be measured in the coming decades.

Policy Interventions to Help Inuit Communities Adapt to Climate Change

We identified and examined how policy intervention can help Canada's Inuit population adapt to climate change. The policy responses are based on an understanding of the determinants of vulnerability identified in ArcticNet supported research conducted with 22 Inuit communities. A consistent approach was used in each case study where vulnerability is conceptualized as a function of exposure-sensitivity to climatic risks and adaptive capacity to deal with those risks. Vulnerability is assessed in the context of multiple stressors, climate and non-climate related, which effect how climate change is experienced and condition adaptation. Case studies involved close collaboration with community members and policy makers to identify conditions to which each community is currently vulnerable, characterize the factors that shape vulnerability and how they have changed over time, identify opportunities for adaptation policy, and examine how adaptation can be mainstreamed. Fieldwork, conducted between 2006 and 2012, included over 745 semi-structured interviews, 35 focus groups/community workshops, and over 107 interviews with policy makers at local, regional, and national levels. Based on a synthesis of findings across the case studies, realizing adaptive capacity and overcoming adaptation barriers requires policy intervention to: (1) support the teaching and transmission of environmental knowledge and land skills, (2) improve access to, and understanding of climate, weather and sea ice information, (3) review and enhance search and rescue capabilities, (4) strengthen harvester support programs, (5) ensure the flexibility of fish and wildlife management regimes, (6) improve the ability of Inuit food systems to meet present dietary and nutritional requirements, (7) protect key infrastructure, and (8) review building codes and land-use plans in light of current and expected climate change.

Inuit Traditional Ecological Knowledge, Subsistence Hunting and Adaptation to Climate Change

The role of Inuit traditional ecological knowledge (TEK) in adaptation to climate change in the subsistence hunting sector was examined among Inuit hunters in Ulukhaktok, NT. Data collection focused on Inuit relationships with the Arctic environment, including hunting knowledge and land skills, and their roles in adaptation to biophysical changes, which affect subsistence hunting. The research found that in several instances TEK underpins competency in subsistence and adaptations to changing conditions including, flexibility with regard to seasonal cycles of hunting and resource-use, hazard avoidance due to detailed knowledge of the environment and understanding of ecosystem processes, and emergency preparedness including knowing what supplies to take when traveling and how to respond in emergency situations (Figure 1). TEK can be considered an element of adaptive capacity or resilience, which is expressed as adaptation if drawn upon to adapt to changing conditions. This depends on the development, accumulation, and transmission of TEK within and among generations.

Several studies and major international climate change reports have identified the importance of TEK in adaptation; however, the role of TEK in adaptation continues to be absent in most adaptation policy processes (Nakashima 2012). Policy-maker discourses are often at odds with local narratives about maintaining livelihoods and give limited weight to the role that TEK can play in adaptation and minimizing risk. Climate change policy in Indigenous regions tends to focus on addressing the risks of climate change directly, rather than building on existing knowledge and practice of adaptation. In northern Canada, climate change adaptation needs to evolve from the identification and description of climate change risks to support practical adaptation entry points including supporting the transmission of TEK (Pearce et al. 2015).

Cultural Context of Food Insecurity Among Inuit in Ulukhaktok, NT

The research examined the cultural context of food insecurity among Inuit in Ulukhaktok, NT. Most literature in the Arctic focuses primarily on the industrial food sector of the food system while ignoring the context in which food insecurity appears. An analysis of the social network of country food exchanges between the 122 Inuit households in the settlement reveals that female-headed households tend to be structurally marginal, with limited access to highly valued, high-quality food. Single male households, however, appear equally marginal, suggesting that food insecurity may be a consequence of changing demographic and economic conditions in the settlement that encourage women to set up households independently of men. We suggest that findings of food insecurity in arctic settlements may be interpreted as a response to the fear of cultural loss as it is to nutritional deprivation.

Vulnerability of an Inuit Food System to Climate and Socio-Economic Changes

Data collection took place between July-October 2014 during which time the researcher conducted participant observation and 40 semi-structured interviews with elders, single mothers, single fathers/bachelors, couples and families with children in Ulukhaktok, NT. Preliminary results show that storage of country foods plays an important role in food security in the community. Households with active hunters own more freezers than the community average for the main purpose of storing country foods. These households are important providers of country foods for households with less freezer space but have also had to limit their summer hunting activities to what can be stored in chest freezers in the absence of a functional community freezer or icehouse. Single mothers and bachelors had less freezer space than the community average and were reliant on sharing freezer space for access to their preferred country foods.

Inuit Women's Conceptualizations of and Approaches to Health

Semi-structured interviews were completed with a representative sample of 31 women in Ulukhaktok, NT or 27% of the female population between May-August 2014. Preliminary analysis of the data shows that Inuit women's conceptualizations of and approaches to health differ in several ways from the dominant paradigm of western healthcare. Respondents describe personal health as being centred beyond the individual, where one's health is associated with that of the familial unit. Spending time with and caring for one's family and maintaining happy relationships are identified as healthy pursuits. In this vain substance abuse emerges as a predominant health concern among Inuit women as these habits consume the funds required to provide for a family and strain relationships. "The land" is identified as central to good health. The land is regarded as the source of country foods, unanimously believed to be the base of a nutritionally and culturally rich diet having ancestral and cultural significance, and contributing to mental and emotional wellbeing and a healthy family dynamic. Women identify environmental and economic stresses that restrict access to the land, country foods and the associated health benefits. Participants express that they are experiencing health effects of this withdrawal such as stress and poor nutrition. Despite medical reports of poor physical health trends in the region many participants report that they have few major health concerns.

Perceptions of Learning Success

Data on perceptions of learning success were collected using semi-structured interviews and pile sorts with southern educators (n= 7), Inuit educators (n=3), Inuit community members (n=8) and Inuit students (grades 9-12) (n= 19) at Helen Kalvak Elihakvik (school) in Ulukhaktok, NT. The data shows that southern educators perceive learning success differently than Inuit. Southern educators perceived learning success as individual means of accomplishment, their responses included examples such as learning literacy skills, working towards a personal objective or building a career. Inuit on the other hand perceived learning success as collective, or contributing to the common good (e.g. family and/or community). Inuit for example, considered success to be a *tilguyuk* meaning a great person, helping the community prosper, hunting and trapping, and encouraging others to pursue happiness. The research confirms discrepancies between southern educators' and Inuit traditional perceptions of learning success. The data suggests that current methods for evaluating Inuit student success, individual standardized testing, are in conflict with Inuit perceptions of learning success.

CONCLUSION

Inuit are highly adaptable to climatic variability, change, and extremes as the research findings indicate. However, financial, institutional, and knowledge limitations are constraining adaptive capacity and increasing exposure-sensitivity to climate change risks. We identified a number of priority areas for reducing vulnerability and enhancing adaptive capacity and generated new information on key determinants of adaptive capacity and adaptation processes. A key characteristic of the findings and related recommendations is that while explored here in the context of adaptation to climate change, they also concern ongoing policy initiatives and priorities in areas of economic, social, health, and cultural development, and can bring immediate benefits in the form of reduced vulnerability to current climatic variability, change, and extremes. What is new is that these issues are re-emerging in the unique context of climate change. As such, there is agreement among many scholars and policy makers that 'mainstreaming' or 'normalizing' climate change adaptation into policies intended to broadly enhance adaptability to risk is likely to be the most effective means of reducing vulnerability to climate change.

Important to all adaptation interventions is that communities and policy makers are actively involved in identifying, proposing, enabling, assessing, and enforcing adaptation policy (Ford and Pearce 2012; Pearce et al. 2012). This is central in linking research to policy. Interventions will be more successful if they are identified and developed in co-operation with local actors and policy makers, who will be more likely to trust them, find them consistent with their goals, norms, and policy objectives. Involving communities and policy makers was a key feature of this research on which policy interventions identified are based on.

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INUIT QAUJIMAJATUQANGIT AND THE TRANSFORMATION OF HIGH SCHOOL EDUCATION IN NUNAVUT

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ABSTRACT

Rapid economic, ecological, and sociocultural changes have serious implications for Inuit communities in the Arctic. Education can provide Inuit with a range of coping skills to adapt to these challenges, such as making more informed decisions, and managing environmental and socio-economic change. Understanding the factors that create educational success for young Inuit will enable school and community leaders to transform schools into meaningful learning environments that provide leadership development so that skilled graduates can become the next generation of Arctic stewards. Our overall goal is to uncover and share successful practices and strategies that contribute to the improvement of high school education in Nunavut. The vision of Inuit education led by Inuit and based on Inuit Qaujimajatuqangit, Inuit ways of knowing and being, is moving forward through recent legislative and policy changes in Nunavut and the implementation of the *National Strategy on Inuit Education*. Our research explores the changes occurring both in Nunavut high schools, and in the lived experiences of research participants. Over the funding cycle, our project has collected stories of Inuit and non-Inuit school leaders who supported young people as they navigated issues of identity in the modern world, and captured the current perspectives of Inuit youth who have experienced high school education. The findings reveal how Nunavut youth are successfully negotiating extraordinary changes in their culture and society and inform us about the future of the Arctic which will be in the hands of these young people. To ensure that the results reach as many people as possible, our team has created bilingual documentary videos (Inuktitut/English and Inuinnaqtun/English). The documentaries, *Going Places: Preparing Inuit High School Students for a Changing, Wider World*; *Alluriarniq–Stepping Forward: Youth Perspectives on High School Education*; and *Millie's Dream: Revitalizing Inuinnaqtun* have been heavily promoted via social and print media and distributed extensively across Nunavut and to Inuit organizations in the South. Results are reaching target audiences, the education stakeholders such as political leaders and policy-makers, and parents, principals, community members, and students. To provide contextual information and statistical profiles that support the interview data, our team has also completed ten-year historical and statistical reports of four high schools in our research communities of Pangnirtung, Clyde River, Rankin Inlet, and Kugluktuk. These reports focus on grades 10, 11, and 12. They reveal information specific to each school and highlight educational indicators such as school attendance, teacher retention, and graduation rates. This project involves a partnership between the Department of Education within the Government of Nunavut, and the Coalition of Nunavut District Education Authorities, which is a territorial organization that represents 26 community groups that represent parental voices in education. The research program emphasizes the involvement of Inuit researchers and community members, responding to community priorities, and returning all the data to communities in ways that communicate the findings and inform all stakeholders.

KEY MESSAGES

- Team members travelled to many national and international conferences to share research findings.
- Building relationships with Inuit and Northern students, and working to develop their skills is a top priority for current research.
- Research continues to involve community consultation, and is built upon a strong foundation of long-term relationships.
- Incorporation of Inuit Qaujimajatuqangit into research practices is important to the long term effect of this project, and to changing ways of researching in the North.
- Bilingual documentary videos continue to effectively share research results to Inuit communities.

OBJECTIVES

1. To contribute to the limited literature on Inuit education by disseminating research findings in reports, articles and peer-reviewed publications co-authored with Inuit educational researchers in Nunavut.
2. To sustain and develop the capacity of Inuit and Northern educational researchers and leaders as they document, analyse, reflect on, and write about policy-based changes and innovations in high school education in Nunavut.
3. To prepare and deliver presentations developed by and with Inuit researchers at a variety of academic, public, professional, and community venues.
4. To ensure Inuit communities benefit from the new knowledge by sharing research findings in an innovative way that is accessible to all Nunavummiut, in bilingual documentary videos.
5. To contribute to research on high school education in Nunavut that identifies strategies and approaches that can improve high school achievement, affirm the positive impact of teaching Inuit language and culture, and having strong Inuit role models in Nunavut schools.

INTRODUCTION

The state of Nunavut education is visible in school statistics that reveal low attendance and graduation rates, low levels of staff retention, and a lack of Inuit teachers, particularly in high schools (Nunavut Tunngavik Incorporated, n.d., p. 13). Education in the new territory has come under scrutiny in the Office of the Auditor General's Report (2013) and much anecdotal evidence in the media about the prevalence of social promotion, low academic standards, and the lack of instruction in an Inuit language during high school grades. These issues are all cause for concern. However, recent public policy developments in Nunavut have created opportunities for Inuit and their non-Inuit colleagues to build a school system based on *Inuit Qaujimajatuqangit* (IQ), traditional Inuit social values and knowledge. The use of IQ in schools is now mandated, but implementing corresponding change takes time, and though improvements are gradually taking place, the current education system is not adequately addressing students' needs or the legislative requirements in the *Education Act* (Government of Nunavut, 2008).

Long-term educational change requires strategic, Inuit-led decisions and actions that improve schools and increase parental engagement in children's education. Extended Inuit families continue to feel the impact of the residential school era and low levels of education create cycles of dependency on social assistance which result in poverty when the cost of living is very high in Nunavut. For parents with negative memories of school, one of the current challenges is to demonstrate the value of education in the lives of Inuit in Northern communities. Working collaboratively with parents, represented by the Coalition of District Education Authorities of Nunavut and Inuit researchers, this high school research is helping to re-build parental supports for education.

Inuit education has also become a key priority across Canada. Under the leadership of Mary Simon a National Committee on Inuit Education (NCIE), representing the four regions in Inuit Nunangat, has developed and is implementing the ground-breaking *National Strategy on Inuit Education* which focused on strategic priorities for change. Improving educational outcomes was described by Simon as, “The greatest social policy challenge of our time” (NCIE, 2011, p. 6). Yet, “There is almost no data or evidence supporting any of the major policy shifts in Inuit education” (NCIE, 2011, p. 90). This lack of data limits the ability of policy-makers to make informed decisions about education.

In Nunavut, policy makers are most concerned about education. Premier, Peter Taptuna, has placed education as a top priority in the new government, because “The situation that we’re in now is rather dire” (Weber, 2013). Nunavummiut realize that education can start to reduce poverty and improve the quality of life, yet exactly how to improve student success remains a complex issue that is now being addressed at the high school level in this research. This ArcticNet research on high schools in Nunavut indicates that improvements in the quality of education, and as a result the success rates of Nunavut high school students, have taken place when committed educators, parents, community members, and students work collaboratively together (Walton et al., 2011; 2012; 2013).

The mandate of this project was to identify best practices in Inuit education at the high school level, and to share them widely and in a way that ensured the people of Nunavut were the main beneficiaries of the research results. In pursuing this goal, our team was committed to increasing the research skills and knowledge of Inuit educational leaders and researchers who must lead change in the future as they are long-term members of Nunavut communities. To achieve results that impact policy, this research was conducted in partnership with the Coalition of Nunavut District Education Authorities (CNDEA), and the Department of Education, Government of Nunavut. The project, and the approach that was taken with respect to the research, provided results and findings that can start to make a contribution to Inuit education policy in Canada, supporting the *National Strategy on Inuit Education* and leading to improvements in the educational levels and social well-being of Inuit.

ACTIVITIES

- Team members travelled to several conferences to share research results nationally and internationally.
- Team members will travel to Gatineau, QC to present two presentations on the current research project at the NS@30 conference, held by the Ottawa-based post-secondary program Nunavut Sivuniksavut.
- Community consultation visits to Qikiqtarjuaq and Pangnirtung contributed to two papers: *Inuit Ways of Knowing, Being and Doing: Creating and Conducting a Community Consultation Process Grounded in IQ (Inuit Qaujimajatuqangit);* and *Inuit Ways of Knowing, Being and Doing: The Creation of a Community School with Elders as Teachers.*
- Researchers contacted Inuit Master of Education graduates, an Inuit and a Northern PhD student to participate in a summer Research Symposium in Ottawa, ON to begin authoring publications based on the research findings. Due to conflicting family demands encountered by several participants, it proved to be difficult to bring the

group together and plans to hold the meeting had to be postponed.

- Due to the cancellation of the summer Research Symposium, a small summer research meeting was held in June 2014, in Toronto, ON to connect research team-members and to plan work for the remainder of the year.
- Another research meeting took place during the Arctic Change conference in December in Ottawa, ON with several research team members attending.
- Analysis of data from 2010 data collection from Clyde River and Pangnirtung, Nunavut revealed a pressing need to focus on the decolonization of education in Nunavut, with a particular focus on Inuit educational leadership, as it relates to the delivery of strong bilingual and bicultural educational programs. These findings will be presented at an International conference in Copenhagen in late March 2015, with submission of a full-text article to the Journal of Youth Studies prior to that date.
- The research team also focused on increasing the research capacity, skills, and knowledge Nunavut Master of Education graduates and team members working at the post-doctoral, doctoral and master of education levels.

RESULTS

Sharing Documentary Videos

Social media continues to play an innovative and successful role in disseminating the findings of our ArcticNet research. By January 26, 2015 the research videos *Going Places* (2011), *Stepping Forward* (2012), and *Millie's Dream* (2013) had a total of 11,024 views. Online views of *Going Places* increased by 37%, while *Stepping Forward* increased by 44%, and *Millie's Dream* by 72%. Total views have doubled from 2013-14 to the current year (see Figure 1). This does not count viewings of the DVD that were widely distributed across Nunavut and other regions and to Inuit organizations across Canada.

Documentary videos were posted on an Internet site with optimized viewing on low bandwidth, Isuma.TV. Videos posted on this site were watched more than those posted on Southern based sites such as YouTube. Comparing the "Nunavut Education" channels on both video hosting sites, the Inuktitut version of *Stepping Forward* (2013) was viewed approximately four times more often on Isuma.TV compared to YouTube (see Figure 2). (Note: *Going Places* was uploaded onto two YouTube channels, "Nunavut Education" and also on the UPEI channel; results in Figure 2 have removed the UPEI channel views for consistency with other documentaries.)

Community Consultations

After successful community consultations in November-December 2013, which gained initial support of local Nunavut District Education Authority (DEA) members in both communities, PhD candidate Cathy Lee travelled again to Qikiqtarjuaq and Pangnirtung from June-July 2014. She was able to meet with 10 community members in Qikiqtarjuaq to further the consultation work on her proposed research topic, *Inuit Ways of Knowing, Being and Doing: Creating and Conducting a Community Consultation Process Grounded in IQ (Inuit Qaujimajatuqangit).*

Lee also furthered discussions on how to proceed with the study on the *Creation of a Community School with Elders as Teachers*. In Pangnirtung, Lee met with nine individuals and also held a community radio show.

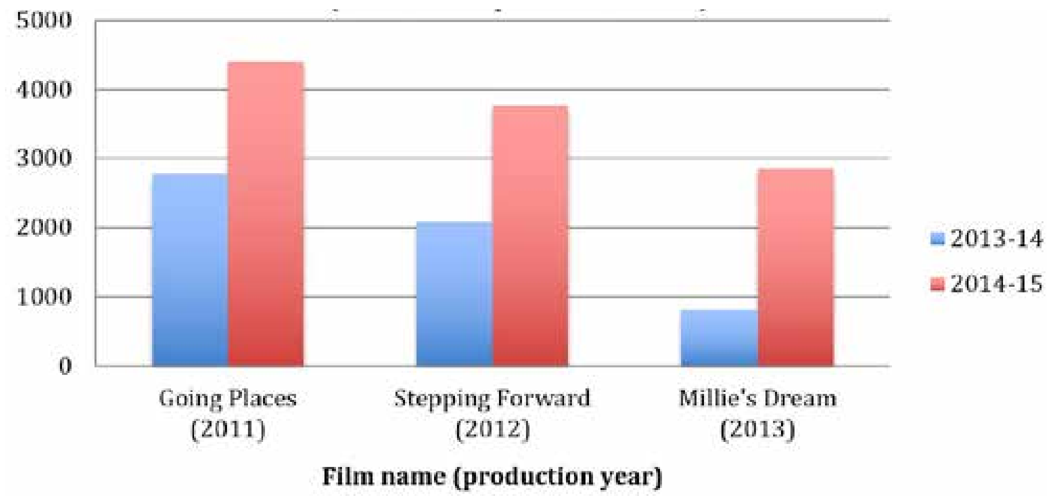

Figure 1. Total views of each research documentary by year.

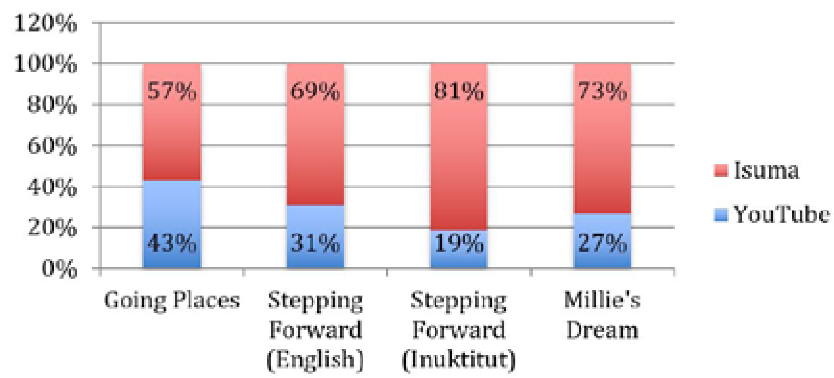

Figure 2. Breakdown of percentage of documentary views by site.

Increasing Research Skills of Team Members

The commitment to improving the research skills of participants and research team members enabled PhD candidate Cathy Lee, a long-term principal and educational leader in Nunavut, to work with experts on the research team. Her studies focus on leadership in quality bilingual education rooted in Inuit Qaujimajatuqangit (IQ) in two Nunavut schools. Support enabled Lee to travel to continue community consultations for her research. She was also able to present at several national and international conferences throughout the year. As a long-term Northern educational leader, and an emerging scholar, the level of knowledge and wisdom she holds on Inuit education is now being shared within her presentations on the development of community based research. The research project also supported Inuit PhD student Naullaq Arnaquq by enabling her to attend academic conferences to expand her knowledge of current research in Inuit Nunangat. Arnaquq chaired two sessions at the Inuit Studies Conference at Laval University and also presented her own research.

Project Meetings

To achieve publication and presentation goals in 2014-15, a five-day intensive Research Symposium was planned to take place in Ottawa, a central location for participants travelling from Eastern and Western Nunavut. The Symposium, organized by Walton, also invited ArcticNet post-secondary researchers Rodon, Abele and their post-doctoral, doctoral and Masters students, both non-Inuit and Inuit. Held in the summer, the Symposium would bring 8-10 Inuit research leaders together with 10 non-Inuit researchers to consider, discuss, interpret and write about the findings from the first years of the high schools and post-secondary research project as they are inter-related. As mentioned above, this Symposium proved to be difficult to organize. Funds designated for the gathering were reallocated and increased time was spent on dissemination of research results at conferences and in publications.

A research meeting was held in December in Ottawa, to coincide with the Arctic Change 2014 conference. The meeting brought together many research team-members including PhD students Naullaq Arnaquq and Cathy Lee, Primary Investigator Fiona Walton, researchers Sandy McAuley and Shelley Tulloch, Nunavut Master of Education graduates Louise Flaherty and Lena Metuq, partner from the Nunavut Coalition of District Education Authorities Nikki Eegeesiak, and Kerri Wheatley, the Project Manager, and an MEd student at UPEI (see Figure 3). At this meeting the team reflected upon the current state of education in Nunavut, along with the research data that had been gathered during this project. The value of these meetings cannot be underestimated as they deepen personal connections, and work towards creating long-term partnerships between Southern-based universities, Northern partners, and Inuit researchers and highly qualified personnel.

DISCUSSION

Using Community Based Participatory Research

The National Strategy on Inuit Education calls for increased research in Inuit education, but also recommends changes in the way research takes place in collaboration with Inuit in Arctic communities. ArcticNet, and the Inuit Tapiriit Kanatami, represented by the Amaujaq National Centre for Inuit Education, hosted a research meeting in Iqaluit, February 19-21, 2013, with Inuit representatives from the four regions, and a group of researchers. Current methodological approaches used in this project support the five recommended principles expressed in the research report:

1. Respect for IQ principals at all stages of the research from design to dissemination;
2. Development of the capacity of Inuit researchers;
3. Investigation of topics important to Inuit communities;
4. Adaption of the project to incorporate community input; and
5. The need for researchers to acknowledge any personal conflicts of interest to research (Amaujaq National Centre for Inuit Education, 2013).

By using decolonizing methodologies and community-based participatory action research to produce four case studies, our team has worked towards furthering research that is respectful towards Inuit communities and based on reciprocal, long-term relationships with Inuit communities and researchers.

Cathy Lee's PhD research supported by this grant is also grounded in these methodologies that are being used in the two communities where she has spent

Figure 3. Research Meeting in Ottawa, December 2014. Back row, L to R: Sandy McAuley, Shelley Tulloch, Louise Flaherty, Cathy Lee, Fiona Walton, Kerri Wheatley. Front row, L to R: Naullaq Arnaquq, Nikki Eegeesiak, Lena Metuq.

over 20 years of her adult life and career. Her research builds upon the relationships she has developed with community members over these years. Lee is working towards a dissertation that ist of benefit to Nunavut education because it represents the wishes and aspirations of Inuit community members and Elders.

Learnings from Cancellation of Symposium

A major lesson learned in the current research year related to the logistical challenges of working with educational leaders in Nunavut. While research participants were eager to contribute to the research project, employment, community, and family demands often meant they could not easily travel away from their homes to participate in research meetings. This challenge is especially prevalent among those educational leaders working in schools.

Having learned this lesson in past years of the project, the current project endeavoured to bring all research team members from the North and South together during a summer month, when schools would be closed. However, coordinating a week-long summer symposium during the precious weeks when educational leaders were free from schools, and wanted to spend some extended periods of time on the land, turned out to be a challenge. Southern-based researchers also had extensive summer commitments to teaching and research and the proposed dates for the symposium coincided with summer holidays for some of the university professors.

The team learned that organizing any activity during the summer months with team members spread across the country, and working in different sectors, is a challenge, and the conflicts between family and community commitments do not make this a desirable time to plan research meetings. Smaller gatherings, possibly close to the ArcticNet Annual meetings or other conference dates are advised for the future.

Inuit Qaujimajatuqangit (IQ) and the Research Project

A key to the success of this research project, and a legacy it leaves for the future, is the importance of incorporating Inuit ways of knowing, doing and being into all aspects of research. The team has worked to embody two IQ principles in particular: Inuuqatigiitsiarniq, and Pilimmaksarniq/Pijariuqsarniq. These research results have not been measured, but they have been mentioned on several occasions by the Inuit and long-term non-Inuit researchers and partners. The noted presence of IQ principles is nevertheless important to the goal of changing the ways in which research is conducted with Inuit in Canada's Arctic regions.

Inuuqatigiitsiarniq: Respecting others, relationships and caring for people

Over the course of this project, research team members have increased their respect and understanding of one another. All team-members have further developed their cross-cultural communication skills. Research has been conducted in ways that have respected not only the methodology of decolonizing research, but in ways that demonstrated respect for Elders, partners, participants, research team members and collaborators. As many team-members were not working full time in research-related professions, contributions to the project were often made on personal time that could have otherwise been spent engaging in family or community activities. The team made strong efforts to ensure that face-to-face meetings were a priority and that emails and many telephone calls were made to check in with individuals about their own lives as well as about the research project.

Pilimmaksarniq/Pijariuqsarniq: Development of skills through observation, mentoring, practice, and effort

The team has worked very closely this year with two PhD students, to offer significant opportunities to engage in research at a high level, as key members of the research team, who are able to direct their own participation in the grant. The project has also worked to create opportunities for Nunavut Master of Education graduates to work with the team as Northern research staff. Inuit MEd graduates were involved in the project as community research leaders, and their leadership was vitally important in helping to provide direction and focus for the project. Often these graduates were supported to attend academic conferences to learn about current research in the Arctic, and contribute to their professional growth.

CONCLUSION

Education is a key determinant of health; raising high school graduation rates leads to improvements in the overall health and well-being of Inuit in Nunavut. Documenting and analyzing the opinions of Inuit education stakeholders provides valuable findings that address the priorities of the *National Strategy on Inuit Education* and the Government of Nunavut. Improving access to research results based on Inuit perspectives on education through bilingual documentary video reaches a wider audience.

Enhancing research skills of Inuit educators and leaders facilitates conversations about educational improvement in *Inuit Nunangat*, builds the capacity of emerging community-based Inuit research leaders and creates a long-term ArcticNet legacy in Nunavut. Research in the extended project will engage stakeholders in discussions of the findings and their impact on educational change in Nunavut. The research highlighted in our documentary videos has identified several factors that contribute to success for high school students, such as the importance of Inuit educational leaders in Nunavut schools, and of the value of Inuit languages. Considering how these factors contribute to long-term change in the system requires strategic consideration in consultation with Inuit educational leaders and policy makers in Nunavut. Stepping back to consider the findings with a group of Northern educational decision-makers and researchers go identify very specific approaches and strategies enable high school teachers to provide supports identified by Inuit students in this research project would be immensely valuable. By continuing to engage Inuit researchers who were closely involved in this research over the last four years, and expanding the team to include experienced Inuit and non-Inuit high school educators in an extended dialogue, the stage is being set for the development of more specific findings based on the research results.

The overall purpose of this research was not to speak on behalf of Nunavummiut, but to present research findings in an accessible way to inform and educate a wide audience and generate important findings related to the achievement of success in high schools in Nunavut.

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We would like to extend a sincere thank you to our many in-community researchers, Northern friends and colleagues. Above all, we are most grateful to each participant who bravely shared their own personal stories.

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SECTION IV. NORTHERN POLICY AND DEVELOPMENT

Section IV is composed of four ArcticNet research projects discussing national and international policies in relation to the Canadian Arctic socio-economic development in a context of the rapid environmental changes and modernization.

THE LAW AND POLITICS OF CANADIAN JURISDICTION ON ARCTIC OCEAN SEABED

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ABSTRACT

The possibility that the Arctic Ocean seabed contains vast deposits of hydrocarbons is attracting considerable attention. Under the 1982 UN Convention on the Law of the Sea (UNCLOS), any state party may, within 10 years of ratifying, seek to extend certain sovereign rights over the seabed beyond its 200 nautical mile Exclusive Economic Zone. To do so, it must establish - through the collection and submission of information concerning bathymetry and geology - that the area of seabed in question is a ‘natural prolongation’ of its landmass. Canada, which ratified UNCLOS in 2003, is mapping the seabed along its northern coastline so that it can submit the necessary infomation to the UN Commission on the Limits of the Continental Shelf. It will do so as a follow-up to its on-time submission, in December 2013, of data concerning the seabed off the Atlantic coast. The United States, Denmark and Russia are undertaking similar exercises. This international, interdisciplinary research project focuses on several existing and potential maritime boundary disputes - involving the United States, Denmark and potentially Russia - that could usefully be resolved before Canada submits a comprehensive package of information to the UN Commission. The resolution of these disputes is highly desirable because the Commission lacks authority to deal with information submitted by a state where it is possible that another state will have a claim to that same area. The project will analyze the legal and political differences involved in the different disputes, explore the various options for resolving them, and provide detailed recommendations. These recommendations will specify a series of considered options occupying progressive positions on the scale of political and technical acceptability. Then, the government of the day will be able freely to select the option that best suits its priorities and objectives, or use the input from this project to craft a better option of its own.

KEY MESSAGES

- This project has explored the law and politics of the Beaufort Sea boundary dispute between Canada and the United States, and identified a number of possible options for a negotiated settlement. Discussions between the two countries are underway.
- This project has explored the law and politics of the Lincoln Sea boundary dispute between Canada and Denmark, and identified a number of possible options for a negotiated settlement. In November 2012, a settlement was achieved, in the form of a provisional boundary line, and announced by the foreign ministers of both countries.
- This project has more recently focused on the Central Arctic Ocean where there are potential overlaps with respect to the extended continental shelf submissions being prepared by Canada, Denmark and Russia to the UN Commission on the Limits of the Continental Shelf. We have been exploring the options available to the three countries, which include the possibility of coordinated or joint submissions as well as the negotiation of provisional or permanent boundaries.
- Significant work has been done with our collaborators in Denmark and Russia. In 2012 a workshop was held bringing together key individuals from the Canadian, Danish and Russian scientific, legal and diplomatic teams, as well as other Canadian and international experts. The workshop contributed significantly towards improving coordination and cooperation between the three countries on this complicated and politically sensitive issue.
- In December 2013, Canada chose to withhold the Arctic portion of its submission to the UN Commission on the Limits of the Continental Shelf, while meeting its deadline by submitting data with respect to the Atlantic coast. Work on the Arctic portion of the submission will continue. This development has made this research project all the more important and topical, since there is time now to re-consider and implement other options for avoiding and resolving potential disputes, and for correcting media and public misunderstandings that could otherwise encourage diplomatic tensions.
- This project has been helping to avoid these misunderstandings and tensions by researching the different options available in the new situation. In March 2015, a meeting was held in Bodo, Norway, involving Christian Marcussen from the Geological Survey of Denmark and Greenland, who led the preparation of the Danish submission in December 2014. Similar meetings with other key actors have been held in Bergen, Oslo, Stockholm, Copenhagen, Washington DC, Novosibirsk, and Ottawa.
- Although it is difficult to prove cause-and-effect between this project and government decision-making, improved cooperation and coordination on this complicated and politically sensitive issue were visible after Denmark filed its submission in December 2014. Although many experts were worried that Russia would react negatively to the fact that the Danish submission included the entire Lomonosov Ridge, the Russian Foreign Ministry instead issued a press release to acknowledge that Denmark was working within the rules and had not surprised Russia in any way.
- This project has resulted in one of the most recent and detailed publications on these topics: a 314-page book entitled “International Law and the Arctic” published by Cambridge University Press. In April 2014, it won the Donner Prize for the best book on Canadian public policy.

OBJECTIVES

- Identify, explore and explain the Government of Canada’s options in the Central Arctic Ocean, where there are potential overlaps between the extended continental shelf submissions being prepared by Canada, Denmark and Russia to the UN Commission on the Limits of the Continental Shelf. Such options include the possibility of coordinated or joint submissions, the negotiation of provisional or permanent boundaries, and recourse to dispute settlement mechanisms such as the International Court of Justice.

- Bring together key members of the Canadian, Danish and Russian scientific, legal and dipomatic teams, as well as other Canadian and international experts, in order to explore the options and promote communication, coordination and cooperation.
- Explain the scientific, legal and diplomatic dimensions of the situation - including Canada's decision to delay the Arctic portion of its submission in December 2013 - to foreign officials, northern indigenous peoples, industry, media and the general public. This explanation includes the options currently open to Canada.
- Explain Denmark's decision, in December 2014, to include the entire Lomonosov Ridge within its submission.
- Explain Russia's conciliatory response to Denmark's inclusion of the entire Lomonosov Ridge within its submission.
- Identify, explore and explain the broader implications of Canada's Arctic boundary disputes for Arctic international relations, including bilateral relations with the United States, Denmark and Russia, multilateral relations within the Arctic Council, United Nations, International Maritime Organization, etc., and last but not least, relations with Arctic indigenous peoples.

INTRODUCTION

This project has proceeded in three stages:

First, we explored the law and politics of the Beaufort Sea boundary dispute between Canada and the United States, and identified a number of possible options for a negotiated settlement. We advised the federal government on this, and discussions between the two countries are underway.

Second, we explored the law and politics of the Lincoln Sea boundary dispute between Canada and Denmark, and identified a number of possible options for a negotiated settlement. We advised the federal government on this, and in November 2012, a provisional settlement was achieved and announced by the foreign ministers of both countries.

Third, we turned our attention to the issue of extended continental shelves in the Central Arctic Ocean and the possibility that two or more of the eventual submissions to the UN Commission on the Limits of the Continental Shelf might overlap to some degree. Our work on this issue included research trips to Russia, Denmark, Norway, and the United States. It included the organization of a closed-door workshop between members of the scientific, legal and diplomatic teams from Canada, Denmark and Russia, along with other Canadian and international experts.

In December 2013, Canada chose to withhold the Arctic portion of its submission to the UN Commission on the Limits of the Continental Shelf. This unexpected development made this project all the more topical and potentially helpful to the Canadian government - since there is time now to re-consider and implement other options for avoiding, managing, and resolving potential disputes over seabed in the Central Arctic Ocean, and for correcting media and public misunderstandings that could otherwise encourage diplomatic tensions.

This project has been helping to avoid these misunderstandings and tensions. In March 2015, a meeting was held in Bodo, Norway, involving Christian Marcussen from the Geological Survey of Denmark and Greenland, who led the preparation of the Danish submission in December 2014. Similar meetings have been held with other key actors in Bergen, Oslo, Stockholm, Copenhagen, Washington DC, Novosibirsk, and Ottawa.

Although it is difficult to prove cause-and-effect between this project and government decision-making, improved cooperation and coordination on this complicated and politically sensitive issue were visible after Denmark filed its submission in December 2014. Although many experts were worried that Russia would react negatively to the fact that the Danish submission included the entire Lomonosov Ridge, the Russian Foreign Ministry instead issued a press release to acknowledge that Denmark was working within the rules and had not surprised Russia in any way.

ACTIVITIES

Michael Byers, Ted McDorman, Suzanne Lalonde and our collaborators continued to engage in analysis, writing and other communications - especially after the December 2013 decision to withhold the Arctic Ocean portion of Canada's submission to the Commission on the Limits of the Continental Shelf, and again after Denmark's December 2014 submission that included the entire Lomonosov Ridge.

They attended international conferences and workshops and held meetings with foreign lawyers and diplomats from Russia, Denmark, Iceland, Norway, the European Union and the United States.

For example, Suzanne Lalonde participated in the 2014 Global Ocean Regime Conference organized by the South Korean government's Maritime Institute, presenting a paper on "Managing Maritime Disputes: The Canadian-American Experience". Professor Lalonde also participated in a closed-door workshop in "L'Arctique sous pression de la mondialisation" with Icelandic President Olafur Ragnar Grímsson in June 2014.

Meanwhile, Ted McDorman continued to advise the Department of Foreign Affairs and International Development on the legal issues concerning extended continental shelves.

In March 2015, as part of the project, a meeting was held during a major conference in Bodo, Norway, involving Christian Marcussen of the Geological Survey of Denmark and Greenland, who led the preparation of the Danish submission. Further meetings with key actors were held in Bergen, Oslo, Stockholm, Copenhagen, Washington, DC, and Novosibirsk.

The three project investigators also participated in meetings and workshops with Arctic indigenous peoples, including Inuit from Greenland and Canada as well as Saami from the Nordic countries.

The project organized a panel at the December 2014 Arctic Change conference in Ottawa to convey its work to the broader ArcticNet community.

In April 2014, the principal published output of this project -- International Law and the Arctic (Cambridge University Press) -- was awarded the Donner Prize for the best book on Canadian public policy.

RESULTS

Our research continues to generate practical results, most notably the November 2012 annoucement of a tentative Canada-Denmark boundary agreement in the Lincoln Sea. We continue to assist the Canadian government with respect to these negotiations, especially concerning the extension of that boundary beyond 200 nautical miles along or near the Lomonosov Ridge. We also continue to assist the Canadian government with respect to its discussions with the United States over the Beaufort Sea boundary, and with Denmark and Russian over future Central Arctic Ocean boundaries. Our efforts to develop a comprehensive understanding of the issues, including the technical scientific and legal details as well as the geopolitical context, are enabling us to identify, explore and explain creative options for win-win solutions that might otherwise not be considered by negotiators.

In 2012, the project organized a closed-doors workshop on Central Arctic Ocean boundaries, designed to assist the governments of Canada, Denmark and Russia indentify opportunities for coordination and cooperation as they prepare submissions to the UN Commission on the Limits of the Continental Shelf. The workshop was attended by two senior diplomats from the Danish Ministry of Foreign Affairs, a senior scientist from the Geological Survey of Denmark and Greenland, two senior diplomats from the Russian Ministry of Foreign Affairs, and a senior diplomat from the Canadian Department of Foreign Affairs - in addition to leading non-governmental experts from the United States, United Kingdom, Australia and Canada.

The project organized a plenary panel on Arctic Ocean extended continental shelves at the December 2013 ArcticNet Annual Scientific Meeting that included Christian Marcussen from the Geological Survey of Denmark and Greenland, Ted McDorman (fresh from his secondment at the Department of Foreign Affairs), Elizabeth Riddell-Dixon from the University of Western Ontario, and Stuart Elden, a world-leading political geographer from the University of Warwick (and the former director of the International Boundary Research Unit at Durham University). In December 2014, the project organized a similar panel at the Arctic Change conference in Ottawa.

James Baker successfully defended his PhD thesis at the University of British Columbia, secured permanent employment at the Royal Military Academy Sandhurst, and is now transforming his thesis into a book for publication.

Michael Byers published a 314-page monograph entitled “International Law and the Arctic” with Cambridge University Press that includes three chapters on Arctic maritime boundaries and extended continental shelves. In April 2014, “International Law and the Arctic” won the Donner Prize for the best book on Canadian public policy.

In short, our project is accomplishing exactly what we had hoped. Our efforts to develop a comprehensive understanding of the issues, including the technical scientific and legal details as well as the geopolitical context, are enabling us to identify, explore and explain creative options for win-win solutions that might otherwise not be considered by negotiators.

DISCUSSION

The media often portrays the Arctic as a region of conflict or potential conflict over sovereignty, jurisdiction, and hydrocarbon resources located in the seabed. To a significant degree, this portrayal is incorrect. All of the land (with the tiny exception of Hans Island) and most of the seabed fall clearly and without dispute within the exclusive jurisdiction of one or another of the Arctic Ocean’s five coastal states.

As part of this project, we drew the possibility of a win-win negotiating solution in the Beaufort Sea to the attention of the Canadian government, which opened discussions on that boundary with the United States. Providing creative legal solutions and feeding them into the diplomatic process has been a major focus of this project. At the same time, our work on the Beaufort Sea boundary included academic publishing: first, a lengthy paper published in Ocean Development and International Law, and then a 314-page book published by Cambridge University Press.

One solution we identified involves drawing a boundary that maximizes the combined area of extended continental shelf susceptible to the assertion of sovereign rights by the two countries. For example, the boundary might be drawn in such a way as to allow the United States to assert jurisdiction over the entire extended continental shelf generated by the Chukchi Plateau, notwithstanding that the equidistance approach would put some of that area beyond U.S. jurisdiction. Similarly, the inclusion of the extended continental shelf within the dispute means that a mutually agreeable boundary could now be drawn that fully respects Canada's legal commitments under the Inuvialuit Final Agreement.

On the other side of the Canadian Arctic, Canada and Denmark had long-disputed 100 square nautical miles of water column and seabed located entirely within the Exclusive Economic Zone (i.e. within 200 nautical miles from shore) in the Lincoln Sea. As part of our project, we identified several options for a win-win solution to this boundary dispute, with one of our members (Ted McDorman) working on these issues while on secondment with the Legal Bureau of the Department of Foreign Affairs.

In November 2012, the foreign ministers of Canada and Denmark announced a tentative agreement on the Lincoln Sea boundary. The only outstanding matters concerns the negotiation of a hydrocarbon-sharing regime between Canada and the Government of Greenland with respect to any deposits that might straddle the new boundary. Our project is now identifying options for extending the new Lincoln Sea boundary beyond 200 nautical miles along or near the Lomonosov Ridge.

Farther out, in the Central Arctic Ocean, it is possible that overlaps will result from the respective submissions made by Canada, Denmark and Russia to the UN Commission on the Limits of the Continental Shelf. Our project is working to identify collaborative options for addressing these possible overlaps, including by negotiating provisional or permanent boundaries in advance of the submissions. We hosted a closed-door workshop on this issue with senior legal, scientific and diplomatic representation from Canada, Russia and Denmark that helped to promote coordination of the different submissions, including the planned limitation of the Canadian and Danish submissions to the west and east sides (respectively) of an equidistance line north of Ellesmere Island and Greenland. More recently, we have been involved in consultations in Moscow, Copenhagen, Reykjavik, Oslo, and Washington.

In December 2013, however, Canada chose to withhold the Arctic portion of its submission to the UN Commission on the Limits of the Continental Shelf. This unexpected development meant this research project became the more topical and potentially helpful to the Canadian government, since there is time now to re-consider and implement other options for avoiding, managing, and resolving potential disputes over seabed in the Central Arctic Ocean.

In December 2014, Denmark filed a submission with the Commission on the Limits of the Continental Shelf that included the entire Lomonosov Ridge, including on the Canadian side of the equidistance line beyond 200 nautical miles from shore, and on the Russian side of the North Pole. Although many experts were worried that Russia would react negatively to the fact that the Danish submission included the entire Lomonosov Ridge, the Russian Foreign Ministry instead issued a press release to acknowledge that Denmark was working within the rules and had not surprised Russia in any way.

In the last few months of this project, we have been assessing the implications of this new development for Canada, and the possibility of new options for coordination and collaboration between Canada, Denmark and Russia on this highly technical issue.

CONCLUSION

This project has contributed significantly to knowledge-generation and policy-making. Our work on the Beaufort Sea boundary dispute between Canada and the United States contributed to the initiation of discussions between those two countries. Our work on the Lincoln Sea boundary dispute between Canada and Denmark contributed to a provisional settlement between those two countries.

More recently, we turned our attention to the issue of extended continental shelves in the Central Arctic Ocean and the possibility that two or more of the eventual submissions to the UN Commission on the Limits of the Continental Shelf might overlap to some degree. As part of this work, we organized a closed-door workshop between members of the scientific, legal and diplomatic teams from Canada, Denmark and Russia, along with other Canadian and international experts. The workshop helped to promote coordination and cooperation during the preparation of the different submissions.

In December 2013, however, Canada chose to withhold the Arctic portion of its submission to the UN Commission on the Limits of the Continental Shelf. This unexpected development makes this project all the more topical and potentially helpful to the Canadian government, since there is time now to re-consider and implement other options for avoiding, managing, and resolving potential disputes over seabed in the Central Arctic Ocean.

In December 2014, Denmark filed a submission with the Commission on the Limits of the Continental Shelf that included the entire Lomonosov Ridge. Although many experts were worried that Russia would react negatively to the fact that the Danish submission included the entire Lomonosov Ridge, the Russian Foreign Ministry instead issued a press release to acknowledge that Denmark was working within the rules and had not surprised Russia in any way. In the last few months of this project, we have been assessing the implications of this new development for Canada, and the possibility of new options for coordination and collaboration between Canada, Denmark and Russia.

ACKNOWLEDGEMENTS

We are grateful to all our collaborators, Canadian or international, as well as the numerous institutions which support their work. We are also grateful to former Foreign Minister Lawrence Cannon, who was receptive to our recommendations concerning Arctic maritime boundaries and opened discussions on the Beaufort Sea (with the United States) and the Lincoln Sea (with Denmark and Greenland), and to former Foreign Minister John Baird for accepting and announcing a provisional boundary agreement with Denmark. Last but not least, we are grateful for the professionalism and commitment of the scientists, lawyers and diplomats working for the Government of Canada on these issues. Their work gives our work meaning, as we seek to facilitate and augment their efforts.

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INTEGRATING AND TRANSLATING ARCTICNET SCIENCE FOR SUSTAINABLE COMMUNITIES AND NATIONAL AND GLOBAL POLICY AND DECISION-MAKING

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ABSTRACT

Ecological change, economic strain, cultural transformation and other factors are significant stressors for the Indigenous peoples of the Arctic. The best available information, based on contemporary science and community and traditional knowledge (TK), must be used to ensure that Inuit and all Canadians can benefit from policy decisions that contribute to sustainable development and the well-being of Arctic environments and peoples. This research project is comprised of a series of sub-projects or activities that examine aspects of the science-policy interface. The central focus is to enhance our understanding of the Arctic policy landscape and factors influencing the translation and transformation of research results into decision support at various levels. It aims to understand how ArcticNet science and IK/IQ (Inuit Knowledge) can, has and might better contribute to informing policies on critical issues such as climate and other forms of change in the future. It is expected that conclusions from the sub-projects will help ArcticNet address the most effective ways to use and translate its research results into 'action' or decision-making at the local, region, national or international levels. More generally, these results will contribute to the present knowledge on how to improve the use, translation and transformation of research results into sound policy or accessible and compelling information for informed decision making in the Arctic or elsewhere in Canada and beyond.

KEY MESSAGES

1. Natural resource development is accelerating across the circumpolar Arctic and sustainable development must resolve health inequities in Arctic populations.
2. Indigenous peoples' engagement is essential to foster sustainable development, and experts participating in focal interviews agreed GIS helps facilitate the adoption of social practices for sustainable circumpolar development.
3. To maximize the benefits and minimize the risks of northern natural resource development, our findings indicate that environmental assessment and regulation of developments should be integrated with public health planning across aboriginal communities in a way that respects and integrates aboriginal priorities and worldviews.
4. Government, organization and agency science advisors play a role in a decision making processes by integrating knowledge from across different stakeholders, sharing relevant information with decision-makers, and catalyzing new multi-stakeholder research initiatives. This process continues to evolve in different jurisdictions across northern Canada, and influences the development of territorial science plans and priorities.
5. A number of factors influence the translation of knowledge from scientific study results to policy or decision on critical environmental issues such as Arctic climate change. An ongoing survey of researchers and policy makers is being completed under this project and results will be released later in 2015.
6. The Integrated Regional Impact Study (IRIS) is one mechanism through which ArcticNet has supported the translation of research results into decision and policy support. Interviews with participants (those engaged in the production of an IRIS report and the intended end users) to the completed IRIS under ArcticNet indicate that, generally, those involved in the process saw it as a useful but challenging exercise in more effective ways of developing, conducting and communicating scientific research to decision makers; end users interviewed were less aware of the process and final products to the point that it clearly indicated that better communication, community engagement, and involvement of regional stakeholders from the beginning of such knowledge translation activities are critical to reach expected goals and support regional decision making or policy processes.

OBJECTIVES

Our project objectives have been broadly focused on obtaining an understanding of where and how science outcomes have the greatest impact and influence on the Arctic policy landscape at different levels, particularly in relation to climate change and adaptation. ArcticNet research has direct and indirect influences on decision making and policy that may be perceived at several levels. We have been conducting activities that are both integrative and specific. Work this past year has been focused on completing previous sub-project data collection and analysis and results communication/ dissemination.

INTRODUCTION

This was the final (extension) year of our project that examined aspects of processes to understand and ensure that investments in research have a larger impact on social, environmental and economic conditions in northern Canada. ArcticNet has often articulated a need to identify critical policy connections or decision making relationships that will contribute to the development and dissemination of knowledge required to formulate adaptation strategies and local, regional, national and international policies to help Canadians face the impacts and opportunities of climate change and globalization in the Arctic (e.g. ArcticNet Strategic Vision, 2006).

Currently, our understanding of how best to effectively translate research results on urgent issues such as climate change into "action" or decision-making at the local, region, national or international levels remains limited. It is important for ArcticNet, as a program, to contribute to and develop a critical understanding of this process in order to make the best use of the knowledge generated under the scientific activities of the program and ultimately, to fulfill its stated objectives and responsibilities to Inuit, other northerners and Canadians in general. To address climate change threats and take advantage of opportunities created in the Canadian Arctic, decision-makers in Canada and the international community need access to the best available scientific research and an innovative method to translate research results into informed policy and other decisions.

The activities that were conducted as part of this project included activities that were both integrative and specific. Activities focused on taking an integrative view of the topic examined the overall science-policy landscape in the context of ArcticNet contributions, while studies looking at the specific scale adopted a case study approach to examine specific and often local impacts of research that can be linked to decision-making and policy. The various sub-projects were clustered into either a: 1) knowledge generation and process emphasis, or 2) policy and decision-making emphasis. In some cases, efforts have been made to also examine these processes at scales that extend from circumpolar to regional.

In each case, we study how the Arctic policy and decision making landscape in Canada is linked to contributions that can be traced to ArcticNet science. A clear understanding of how current and new information is informing policies and actions on climate change and adaptation will be useful for ArcticNet researchers in their attempts to effectively convey information to decision-makers and positively influence future action. This project has not acted as an evaluation of the relevance or effectiveness of any one approach, but rather provides a framework for understanding which steps and factors in the knowledge translation process are most important or influential for this area of science to policy translation. It takes advantage of the opportunity the ArcticNet program has created to study the intersections among knowledge and decision making communities, and to enhance the abilities of both scientists and decision makers to improve knowledge exchange and utilization in the future.

Although the core funding for this project ended in 2013-14, we applied residual carry-forward funding to complete ongoing work, and we report on our progress for those activities here. All of this research has been cumulative and linked to previously reported work, and will continue to be developed further in the coming year.

ACTIVITIES

Activities under this project have been organized into sub-projects. Over the life of the project we have pursued 10 unique sub projects focusing on either integrative or specific scales. The sub projects included the following:

- **Sub-project 1**: ArcticNet's IRIS Process as a Science-Policy Mechanism: A Case Study of IRIS 4 in Nunavik and Nunatsiavut.
- **Sub-project 2**: Understanding Scientist and Decision Maker Perspectives on the Arctic Science-Policy Landscape.
- **Sub-project 3**: Barriers and Facilitators to Indigenous Knowledge Incorporation in Policy-Making: The Nunatsiavut Case.
- **Sub-project 4**: Role of GIS in Health Impact Assessment Processes for Natural Resource Development in the Canadian Arctic.

- **Sub-project 5**: Community Adaptation Planning in Nunavut.
- **Sub-project 6**: Sharing Research Findings in the Canadian Arctic: Assessing the Integration of Community-Based Knowledge in Policy Communications about Climate Change Related Food Insecurity.
- **Sub-project 7**: The Role of Science Advisors in Facilitating Science-Policy Linkages.
- **Sub-project 8**: Assessment and Indicators of Arctic Science Impact.
- **Sub-project 9**: Quantitative Analysis of Linkages between Policy and Knowledge during the first cycle of ArcticNet Using Analysis of Parliamentary Hansard.
- **Sub-project 10**: ICC Consideration and Development of a Position on Oil and Gas in the Arctic.

Activities on sub-projects 5,6 and 10 were reported on in detail in the 2013-14 report. While publication efforts continue on those sub-projects, the focus of efforts in 2014-15 was on sub-projects 1-4 and 7-9 and those activities and results are presented here.

1. ArcticNet's IRIS Process as a Science-Policy Mechanism: A Case Study of IRIS 4 in Nunavik and Nunatsiavut (Furgal, Hik, Nickels, Buckham, Kelley, Moss-Davies, Braithwaite)

All interviews with end-users were completed; transcripts were verified by all participants; transcripts were then coded in NVivo analytical software. Qualitative analysis was completed and preliminary reporting has started. A poster was presented at Arctic Change 2014 on the results of this sub project that explored developers and end-users' perspectives of the value, challenges and benefits of the IRIS process as a science-policy interface mechanism. Final reporting is being completed and publications are now being prepared on this work.

2. Understanding Scientist and Decision Maker Perspectives on the Arctic Science-Policy Landscape (Furgal, Buckham, Hik, Nickels, Moss-Davies, Braithwaite)

After piloting the survey with decision makers at the 2013 ArcticNet Annual Scientific Meeting adaptations were made to the survey questions and structure.

The survey was uploaded to Qualtrics survey software and underwent a pilot distribution in summer 2014. Further adaptations were made to the length of the survey and it was released to targeted individuals in winter 2015. We must now increase the survey distribution to significantly increase the sample size of respondents prior to finalizing the dataset and beginning analysis.

During Arctic Change 2014, we organized a panel session (with six presentations) on "The Interface Between Science and Policy in the Arctic: New Perspectives on Knowledge to Action". This session was co-chaired by David Hik, Chris Furgal, and Aynslie Ogden.

3. Barriers and Facilitators to Indigenous Knowledge Incorporation in Policy-Making: The Nunatsiavut Case (Buckham, Furgal, Sheldon)

A final report was distributed to study participants and Nunatsiavut Government representatives in spring 2014. Since that time two manuscripts have been prepared and are in revision for submission to scientific journals.

4. Role of GIS in Health Impact Assessment Processes for Natural Resource Development in the Canadian Arctic (McGetrick, Hik, Bubela)

McGetrick completed her thesis in June 2014. Since then two manuscripts have been submitted and a third is in final preparation (Environmental Health Perspectives, "Geographic Information System Support for Public Health Planning of

Natural Resource Development in Northern Canada" (McGetrick, Bubela, Hik).

7. The Role of Science Advisors in Facilitating Science-Policy Linkages (Hik, Morris, Ogden)

One manuscript is in preparation from this work.

8. Assessment and Indicators of Arctic Science Impact (Furgal, Hik, Braithwaite, Meakin, Nickels, Moss-Davies, Durkalec, Buckham)

Using the framework developed through the poster preparation we have been working on one manuscript and preparing funding applications to apply/ groundtruth the framework using past projects in the Canadian Arctic.

9. Quantitative Analysis of Linkages between Policy and Knowledge during the first cycle of ArcticNet Using Analysis of Parliamentary Hansard (Hik, Morris, Bubela, Bieber)

Analysis and summary of Canadian IPY and ArcticNet Publications and searches of the Hansard databases – House of Commons, Senate, Yukon, Northwest Territories and Nunavut are now complete, and a manuscript is in final preparation.

RESULTS

1. ArcticNet's IRIS Process as a Science-Policy Mechanism: A Case Study of IRIS 4 in Nunavik and Nunatsiavut

A total of 11 of 12 IRIS 'developers' (researchers or regional decision makers involved in the development of the IRIS content and reports) and 7 of 26 invited intended end users participated in interviews to share their perspectives on the IRIS as a science to policy translation mechanism.

The majority of perspectives shared on the IRIS process and its perceived impacts on policy and decision making in Nunavik and Nunatsiavut came from individuals involved in the development of the IRIS reports. The majority of intended end-users that did not accept the invitation to participate in the study did so because of a lack of knowledge and awareness of the process and final report/products. Five of the 7 end users participants were unaware of the final IRIS report but had some knowledge or awareness of the process that had taken place.

Perspectives on the IRIS process as a mechanism to enhance the potential for ArcticNet science to have influence on regional decision making and policy were grouped under three major headings.

Learning

Among those involved in the IRIS process, one regional decision- maker felt that participants to the process had learned interesting ideas from other regions, that the process reinforced existing relationships between themselves and researchers, and that the process may have impacted policy priorities, but that this was very difficult to assess. Researchers talked about developing broader understandings of the North, of the 'human components' of research, and of the complexities of working in collaboration with others. These participants also identified learning about the benefits of outreach, local input into research and processes of knowledge dissemination, and identifying potential areas for future research as a result of their involvement in the IRIS process. Only one developer spoke about learning more about policy-making through the IRIS process. Most participants indicated that being involved with the IRIS impacted how they conducted their research, how they communicated or engaged with policy makers, and felt that the process had impacted policy priorities.

Goals

Almost all IRIS developers felt that the IRIS 4 process met the goals of promoting and informing the use of science in policy- and decision- making in Nunavik and Nunatsiavut, though some pointed out that this would be difficult to assess and show evidence of.

Roles

About half of developers felt that the current role of ArcticNet was to 'bring everyone together' or link governments, communities and researchers. Others felt that the program was to have a significant impact on decision-making in the North; and finally, others felt that the expectation of impact was limited to more specific initiatives.

About half of end-user participants to interviews thought that ArcticNet had a significant role in coupling local knowledge with science, and in supporting evidence-based decision-making. The remaining half saw ArcticNet as having a limited role, acknowledging that science and traditional knowledge can conflict with one another, and that negotiating knowledges process was something that required greater attention.

All developers felt that ArcticNet had some role in supporting the incorporation of science into policy- and decision-making, though some pointed out that it is not feasible to expect this from one science program alone. Developers felt that this responsibility lay with policy makers, scientists, both policy-makers and scientists, or research programs. The majority of end-users saw this as a regional governments' responsibility, while some saw it as a job for researchers and decision-makers together.

2. Understanding Scientist and Decision Maker Perspectives on the Arctic Science-Policy Landscape

Two rounds of pilot testing of the 31 question survey examining perspectives among researchers, decision makers and intermediary organizations on the factors that influence the processes of translating knowledge from scientific results to policy and decision making support have taken place. The second pilot testing round further reduced and adapted the survey to ensure greater clarity and efficiency in response times. The survey was distributed to a small group of potential participants and due to its length is receiving a poor response rate. Further reduction of question length has occurred and a final version of the survey will be more widely distributed in spring 2015. All respondents to date have shown interest in the topic and questions, but found the tool too detailed and long to encourage participation. Topics included in the survey are:

Perceptions on current use and impact of science on policy; perceived success and frequency of success in science impacting policy; satisfaction regarding elements of the science – policy interface; perceptions on barriers to science impact on policy; perceptions on strategies that promote/support impact of science on policy and perspectives on communication and information exchange at the interface.

During Arctic Change 2014, we organized a panel session of six presentations on "The Interface Between Science and Policy in the Arctic: New Perspectives on Knowledge to Action". This session was co-chaired by David Hik, Chris Furgal, and Aynslie Ogden. Presenters discussed successful case studies of science-policy interaction, indicators of success at the interface, technologies to support this knowledge translation and challenges encountered when bringing together scientists and policy/decision makers.

3. Barriers and Facilitators to Indigenous Knowledge Incorporation in Policy-Making: The Nunatsiavut Case

The results of this research were presented in detail in the 2013-14 report. The final report was disseminated to participants and Nunatsiavut Government representatives in 2014 and work continues on revisions to two journal articles for publication based on the framework developed and the results of the case study on the Nunatsiavut Government's development of an Environmental Protection Act and the role of Inuit Knowledge in that process.

4. Role of GIS in Health Impact Assessment Processes for Natural Resource Development in the Canadian Arctic

Natural resource development is accelerating in the circumpolar region, raising questions about the balance between potential economic benefits for northern indigenous peoples with the risks of increasing long-standing health inequities. New communication tools are needed to document and synthesize complex and diverse evidence of health impacts in natural resource management forums. This research examines the perspectives of circumpolar experts on indigenous community engagement that employs Geographic Information Systems (GIS), reflecting the relevance of indigenous health concepts in discussions about land use and development. Thirty policy-makers, academic researchers, and community practitioners participated in semi-structured interviews interrogating social practices around GIS, indigenous health, natural resource development, and community health systems. Qualitative analysis of the interview transcripts for key themes indicated that the majority of circumpolar experts supported employing GIS to facilitate more extensive collaboration with indigenous communities and to produce higher quality data outputs. To ensure GIS enables improved public engagement on the health impacts of development, the experts recommended increasing communities' access to technology and training, community stewardship of data, utilizing data for ongoing monitoring of development impacts, and coordinating cumulative impact monitoring within regions. Findings focus on informing natural resource management forums in Arctic and subarctic Canada, but also consider relevance to other circumpolar regions for fostering sustainable development with greater accountability to local indigenous populations. A summary of some of the informative responses relevant to the use of GIS in circumpolar communities are summarized in Table 1.

We also examined how aboriginal people identified health and socio-economic impacts during public hearings for environmental assessments of two mines in the Northwest Territories, Canada. We analysed public hearing transcripts and reports of environmental assessment using: researcher-driven document review, sentiment analysis, term frequency-inverse document frequency analysis, stakeholder grade level and proportions analysis, and correspondence plotting analysis. We assessed the content, communication practices, and linkages between process and outcomes during the environmental assessments. Aboriginal participants in the public hearings emphasized health and socio-economic content, expressing broad socio-ecological perspectives. Other stakeholders in the public hearings, including regulators, federal and territorial governments, and industry proponents, presented only limited engagement with aboriginal participants in their respective communication practices. This separation of language and perspectives is represented graphically in Figure 1. To maximize the benefits and minimize the risks of northern natural resource development, our findings indicate that environmental assessment and regulation of developments should be integrated with public health planning across aboriginal communities in a way that respects and integrates aboriginal priorities and worldviews.

7. The Role of Science Advisors in Facilitating Science-Policy Linkages (Hik, Morris, Ogden)

Some governmental jurisdictions now have a single person who is responsible for managing the coordination of scientific information and providing scientific advice to the leaders of their government. The federal government, the territorial governments (Yukon, NWT and Nunavut) and all but three provincial governments were included in this evaluation. Nova Scotia, New Brunswick and Prince Edward Island were excluded because their locations preclude North/Arctic science concerns. In smaller jurisdictions, such as the territories, the government investment of funds is smaller and more strategic (tied to local concerns and needs). They are actively pursuing relationships with outside, non-government entities to build capacity (e.g. GNWT and Wilfrid Laurier University partnership), issuing licenses/ permits for research and administering funds from

Table 1. Geographic Information Systems in Circumpolar Communities. Note: PM=Policy maker; R=Researcher; and P=Practitioner.

Source	Quotation
"Self-Determination and Capacity Building"	
R-5	GIS is one way to really look at the footprint or the nature of [a] project's activities' … are there river systems, or water supplies, where you have, let's say, regular fishing spots, regular cabins, that are connected somehow to a project site? Is there a potential vector for health impact?
P-6	It was post-Delgamuukw, which was a big court case around trying to prove title … people weren't sure about exactly how some of the "adaawk", or the traditional stories… related to use on the land. I was part of a group that was using GIS to actually track some of that.
P-7	We deal everyday with individual residents, villages, [government] agencies, national and multinational interests … land use planning, permitting, and zoning … to negotiate, and avoid potential conflicts … it's within that context that [the] mapping project becomes a decision support tool to assist our land use planners … to protect subsistence.
P-8	This is a tool to help [indigenous peoples] become more efficient and effective in governing. Not only their people, but their lands, and the different activities that take place on those lands. Whether it's … planning, or managing their natural resources ... rural housing … the emergency 911 system. GIS can be used for all those different things.
R-6	[Indigenous people] can arrange their own health system [with] their definitions of health and healing, which might be very different from the biomedical, [and] come up with their own models to improve the overall health situation … they create maps, for example, for preventative health interventions in the community
R-7	I know from talking to people [that] they are interested in GIS [as] tools that they can actually use themselves, on their boats and snowmachines, and being able to provide that information … there is a lot of room to do really interesting and creative things.
PM-2	[U]niversities, federal agencies, local [communities], some consortium that would put together workshops and training sessions, that would probably be most effective … a collaboration of efforts really does need to take place.
"Community-Based Research by Government and Academia"	
PM-4	[H]ealth problems in the Arctic are quite significant, quite extraordinary, and quite different in many ways ... it's a difficult place to do research. It has to be community-based.
R-8	[C]onnecting the dots between that motivation, and that interest, and the ability to actually do it … working with partnerships over a long time … that really helps to build the capacity at the community level.
P-9	[Our] database [is] a key research tool for us, and a key communication tool for us. It's how we can summarize, in an accessible way, the information that we collect, which is extremely fine grained, and detailed, and extensive.
R-9	[I]f they ask a question, and you give them the answer, that's probably more important than them actually having the data in their memory stick … it is a major ethical concern, data ownership and access in a group.
R-10	[T]he Saami, … to prevent a gold mine from occurring on their traditional reindeer herding lands, they used the data, directly, themselves, and then … informed us that they had done that already. It is the community that utilizes it.

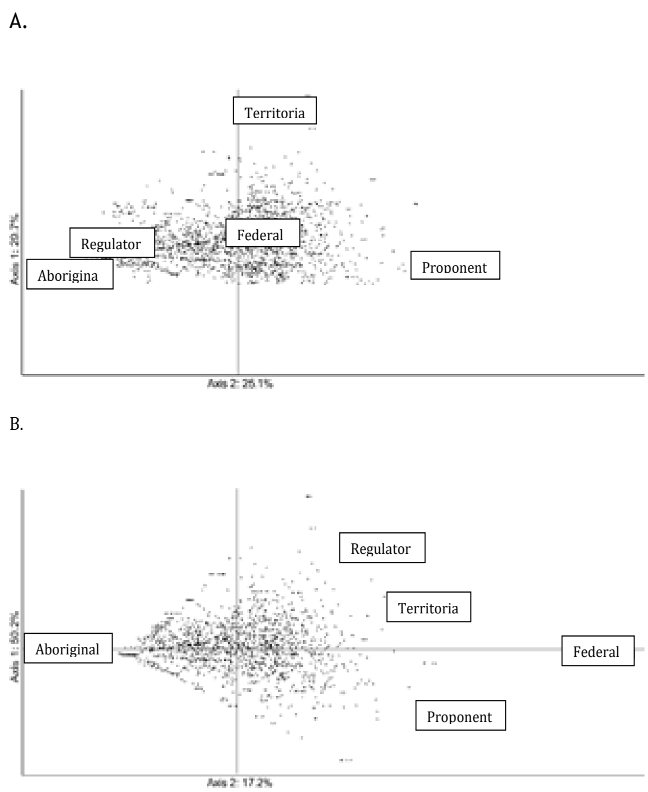

Figure 1. Correspondence plot of public hearing transcript texts by stakeholder group for A. Prairie Creek mine and B. Nico mine.

the federal government for specific research projects and initiatives. Including aboriginal/local knowledge and participation into the science process appears to be central to the territorial governments' approach. Overall, science advisors appear to be successful in building strong partnerships with other governments and organizations to address issues such as adapting to climate change.

8. Assessment and Indicators of Arctic Science Impact

A framework and series of metrics were developed based on a review of the literature in this field and adaptation and organization of metrics for their applicability to Arctic science. We have been working on one manuscript presenting this framework and preparing funding applications to apply/groundtruth the framework using past projects in the Canadian Arctic. The framework includes measures of impact of the investment in Arctic science on: 1) advancing knowledge, 2) enhancement of future research capacity, 3) informing policy and decision making, 4) society and culture, 5) the environment and 6) the economy. The framework draws upon previous work in this area in other countries and is proposed as possibly more comprehensive way of assessing contributions from the investment in and conduct of Arctic science.

9. Quantitative Analysis of Linkages between Policy and Knowledge during the first cycle of ArcticNet Using Analysis of Parliamentary Hansard

Using the terms 'ArcticNet' and 'International Polar Year' (IPY) we examined the relationship between the frequency of publication of scientific results in peer-reviewed formats with the level of recognition of large Canadian Arctic science programs in the media and in the deliberative bodies of the federal and territorial governments (Hansard transcripts) over the past decade. Analysis of the Hansard databases (2000-2012) does not indicate any sustained discussion of Arctic science. While the Arctic and its inhabitants are referenced in the Senate, House of Commons, and legislatures of Nunavut, NWT and Yukon, science and research are not central themes. A separate search of Government of Canada press releases from 1/1/2002 to 31/12/2012 identified a total of 793 releases containing the word 'Arctic'; of these 9 referenced ArcticNet and 47 referred to IPY. We concluded that it is difficult to identify direct connections between two research programs that generate knowledge (e.g. ArcticNet, IPY) and knowledge consumers at the level of government decision-making. While there is often a close connection between the publication of scientific results and media or public interest, this is not often reflected in political discourse, at least in Hansard records. The exchange of information likely takes place informally or in committee, and only the outcomes are visible after the fact. Further investigation, involving the consumers or synthesizers

of specific Arctic science and knowledge is necessary to understand how to ensure that pathways between research programs that create knowledge and users of this same information are strengthened. The role of science advisors, both within government agencies and externally, in mediating this transfer of knowledge may also be critical (see sub-project 7, above).

DISCUSSION

The policy and/or social benefits arising from innovative research can be challenging to identify and quantify. When attempting to examine the relationship between knowledge production and use in the North this is further challenged by limited data availability, incompatibility between databases and analytical tools or metrics, and difficulties in tracking traditionally oral sources of knowledge into decisions at various scales (e.g. IK into policy).

Under components of this study we have examined the environment in which these two communities (knowledge producers and knowledge users) interact, the processes used to facilitate their interactions and exchanges, the mechanisms through which they share information and various actors' perspectives on the things that influence these interactions and their 'success'.

The central objective of ArcticNet, as stated in the original proposal to the Network Centres of Excellence Program and as stated in the ArcticNet Strategic Plan (2006) is to contribute to the development and dissemination of knowledge needed to formulate adaptation strategies and national policies to help Canadians face the impacts and opportunities of climate change and globalization in the Arctic. Traditionally, the assessment of the development and dissemination of knowledge products (journal articles, presentations, etc) in the research community has received significant attention and has been relatively easy to achieve. However, measuring where this knowledge ends up and by whom and how it is used, if at all, presents significant challenges such that an evaluation of the attainment of a program goal that includes measures of impact on policy and decision making is very difficult to conduct. What we have been able to show at various levels, is that a number of different factors influence the knowledge translation process between communities in different circumstances. A number of mechanisms and technological tools are showing promise in facilitating and enhancing that KT process yet if we are interested in 'measuring' this impact we must realize that there is often a significant delay between the act of knowledge production and dissemination and the appearance of 'evidence' of uptake and use in some form.

Despite this, our results suggest several ways that research can support the national, regional and local climate change adaptation policy and program interests of Canadian Inuit. It has been essential to consider how various stakeholders understand and communicate about the relationship between climate change, country foods, and health. Increasingly, researchers are seeking out Indigenous sources of knowledge about what adaptation strategies are best suited to a changing northern environment. However, what is less clear is how findings from these Indigenous knowledge studies are integrated back into climate change policy-making.

Overall, it appears that we are able to utilize new and existing conceptual frameworks to help us understand, and possibly improve or enhance the science-to-policy knowledge translation process in the Arctic. It appears that research outcomes that are timely, clearly communicated through known channels, and can be directly related to current policy objectives for which there are existing information needs, will have the greatest probability of having impact on policy and decision makers, at local, regional, national and international levels. Improving those aspects of the science to policy chain (timeliness of research, focus of research in relation to policy goals and information needs, increased opportunities for researcher - policy maker interaction etc) can enhance the potential role and influence that future Arctic science can have on northern policy and decision making.

CONCLUSION

Many of the original project objectives have been achieved or are close to being met, and key publications are submitted or in preparation. Our results show that ArcticNet research is both directly and indirectly, however sometimes not obviously, utilized in decision making by various groups in the North and for various purposes. Being able to track these influences is a critical step in making science more useful for formulating policy, and to enhance it's contributions to aspects of society, culture and the economy at various scales. Because of the lag in time between knowledge production and dissemination activities and incorporation of results into science policy, an examination of the evidence to track the influence of Arctic science on policy and decision making needs to be considered in terms of a decade and not years. However, with continued efforts in this area of research there is the opportunity for significant learning that has the ability to positively influence science program activities in ways that enhance the likelihood for the knowledge generated to support and inform policy and decision making in the future.

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PUBLICATIONS

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Buckham, M., Furgal, C., 2015, Indigenous Knowledge Incorporation in Policy Making: a framework tool for policy makers, in preparation to be submitted summer 2015.

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THE EMERGING ARCTIC SECURITY ENVIRONMENT

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ABSTRACT

Climate change, undefined or disputed boundaries, access to resources and newly viable transportation routes and governance issues are generating significant questions about Arctic security and circumpolar geopolitics in the twenty-first century. Anticipating future prospects for competition, conflict and cooperation in the region requires a systematic examination of the new forces at play, both internationally and domestically. Our project examines fundamental questions including: What is Arctic security? What will the circumpolar world look like in the future, given the various forces transforming the region? Our project poses these questions at the international and national levels to discern what senior government officials, Indigenous groups, corporate interests, scientists, academics, and Northern residents perceive to be the most significant security and safety challenges in the Arctic - and to determine what unilateral, bilateral and multilateral mechanisms should be in place to address them. This project makes two primary contributions: one policy focused and the other academic. First, it adds to the public policy debate about the evolving Arctic security environment. Our research team critically assesses the interplay between traditional, state-based military security and environmental, health, and societal security concerns. In linking international and domestic security practices to human impacts, we are producing more integrated frameworks and tools to anticipate the consequences of security action/inaction on Northern ecosystems and peoples. This should help to enhance Canada's capacity to deal with opportunities and challenges in a way that is sensitive to, and better integrates, Northerners' concerns and priorities. Second, this project advances academic debates about the relationship between environmental, diplomatic, political, and socio-economic processes and ideas about Arctic security. Community consultations, participation in the Arctic Security Working Group, as well as partnerships with federal departments and agencies ground our analyses of how the changing geopolitics of the Arctic are influencing government policy and affecting Northerners' culture, well-being, and economy. As a team, and in collaboration with our partners, we are refining existing frameworks and models to incorporate the complexity of these new forces, to better explain the actions that are now being taken, and to generate appropriate lessons for future relationship-building.

KEY MESSAGES

- The Arctic sovereignty and security environment has continued to generate Canadian and international headlines over the past year, with Russian aggression in Ukraine provoking debates about whether this portends similar aggressive behavior in the Arctic, and the Danish submission of its extended continental shelf claim in the Arctic basin resurrecting debates about the "ownership" of the North Pole.
- The Arctic continues to pose unique challenges that require innovative, comprehensive approaches to synchronize efforts and address security and safety threats/hazards in a timely, efficient, and credible manner that promotes national goals of regional prosperity and stability and is responsive to Canadian interests and values.
- Developing the right Canadian Arctic foreign, defence and security policies (including confidence-building measures in the region) and translating them into appropriate facilities, equipment and practices requires a long lead time that is not factored into most academic discussions.
- Canada and the United States should enhance their longstanding partnership in the Arctic defence and security domain and should continue communicating with one another on matters related to Arctic sovereignty to avoid political misunderstandings and ensure proper surveillance, Arctic domain awareness, and appropriate enforcement capabilities in an austere fiscal environment.
- Our academic work and publications aimed at popular and specialized audiences, as well as our presentations to security practitioners, parliamentarians and other decision-makers, seek to engage, respond to, and shape academic and stakeholder opinion on Arctic sovereignty, security, and safety issues in their many facets.

OBJECTIVES

1. To continue to monitor and critically examine Arctic state practices in the defence, security, and safety spheres across the spectrum of "whole of government" relationships and activities.
2. To continue to analyze evolving relationships between the Canadian Armed Forces, other federal government departments and agencies with security mandates, other Arctic and non-Arctic states, and Arctic peoples.
3. To develop and enhance models that inform the framing and implementation of defence and security policies and that promote relationships that contribute to and support the interests of Canadians living in Arctic communities.
4. To provide opportunities for emerging scholars to contribute to academic, policy, and public debates on the sovereignty, defence and security interests of Canada and the other Arctic states.
5. To continue to critically examine the interests of non-Arctic actors in the region and how these interact with defence, sovereignty/territorial integrity, and security considerations.

INTRODUCTION

The complexity of the changing Arctic security environment requires an interdisciplinary approach (history, political science, law, geography, etc.) that blends realist, liberal internationalist, and constructivist approaches. The traditional view of security in the Arctic region has focused primarily on military defence, particularly the protection of national borders and the assertion of state sovereignty. This view is habitually seen as distinct from local, Northern, and Indigenous understandings of security that emphasize economic, social, cultural, and environmental concerns. Similarly, national discussions of "Arctic sovereignty" tend to focus on outstanding maritime boundary disputes and perceived foreign threats to territorial integrity and control over resources, while Northern perspectives emphasize that "sovereignty begins at home" – that sovereignty is better understood as encompassing a wide range of daily activities practiced by local inhabitants within the Arctic region. These different frames, understandings, and concepts are distinct but not mutually unintelligible, though they do sometimes conflict.

Policy trends over the past decade indicate a strong trend toward international cooperation and more closely integrated domestic efforts, as identified in *Canada's Northern Strategy* – although members of the project team continue to disagree on whether external developments (particularly Russian aggression in Ukraine) will or should substantively undermine or disrupt this cooperative atmosphere. Although official Canadian assessments do not anticipate any conventional military threats to the region, they do foresee a rise in security and safety challenges that require an integrated Whole of Government (WoG) or Comprehensive Approach.

ACTIVITIES

ArcticNet funding has facilitated a wide range of research and dissemination activities over the past year. This has enabled network researchers, as well as a broad array of graduate students and postdoctoral fellows, to achieve our project's overall research objectives, gather information relevant to ongoing research projects, and disseminate research results to academic, popular, and political/policy audiences.

Whitney Lackenbauer, Rob Huebert and Suzanne Lalonde continue to serve as the three academic representatives in the Arctic Security Working Group (ASWG), a biannual forum co-chaired by Joint Task Force (North) and the northern regional office of Public Safety Canada in Yellowknife. The working group brings together officials from federal and territorial departments and agencies, Aboriginal leaders, and international partners to discuss sovereignty and security issues and to enhance information-sharing and cooperation. ASWG meetings provide Lackenbauer, Huebert and Lalonde with insight into government priorities, provide a forum for making contacts, and offer them an opportunity to share Arcticnet research findings and contribute to policy discussions.

Huebert, Lackenbauer, and Lalonde participated in the Third Sino-Canadian Arctic Exchange in Shanghai, China, in May 2014. This allowed them to continue an ongoing dialogue with leading Chinese academics and policy-makers on Arctic affairs. These activities have also supported various publications, including Lackenbauer's forthcoming monograph with James Manicom and Frédéric Lasserre (lead of the Arcticnet shipping project) on China's Arctic interests and how they affect Canada.

Members of our research team also received frequent requests to share their expertise on Arctic sovereignty, security, and governance topics with politicians and policy-makers in Canada and abroad. For example, Lackenbauer and Huebert appeared as witnesses before the House of Commons Standing Committee on National Defence on Arctic security and North American defence issues in Ottawa on 9 December 2014. Lackenbauer's international travel included trips to Madrid at the invitation of the Canadian embassy to present to a leading Spanish think tank, defence and political officials, and Spanish scientists and diplomats. At the request of the Embassy of the Kingdom of Denmark in Ottawa, Lackenbauer was one of two academic experts invited to a private dinner meeting with the Danish Foreign Policy Committee on 19 June 2014 to discuss Arctic security and Canada-Denmark relations.

Lackenbauer continued to conduct research and interviews with federal and territorial officials in Canada pursuant to his work conceptualizing and analyzing a Whole of Government/Comprehensive Approach to Canadian Security and Safety in the Arctic. He also continued to work closely with various military officials and other security practitioners to identify historical and contemporary “lessons learned” that will help to inform current and future policies and practices. He has enjoyed ongoing discussions with Canadian Rangers, and was invited by the Department of National Defence to attend Operation Nanook as a VIP Observer in Iqaluit in August 2014. He continues to advise the Canadian Armed Forces, federal departments, and other stakeholders on Arctic security issues, appeared on several radio programs, was frequently interviewed for newspaper and magazine articles about Northern sovereignty and security topics, and lectures frequently in Canada, the United States, and Europe on Canada’s Arctic strategy and related security issues. In the summer of 2014, he participated in the Students on Ice expedition to Nunavik, Nunatsiavut, and Greenland, exchanging knowledge on Arctic issues with high school students and expert staff. He was invited by the Department of Foreign Affairs, Trade and Development and Canadian Forces College to deliver courses on Arctic Governance for foreign service officers, military officers, and other federal officials, which drew upon knowledge and expertise generated by his ArcticNet research. Furthermore, Lackenbauer was also contracted by the Department of Foreign Affairs, Trade and Development to serve as facilitator of the Enhancing Permanent Capacity at the Arctic Council Workshop, convened by the Canadian Chair of the Senior Arctic Officials, in Yellowknife on 20 October 2014. All of this knowledge-to-action activity builds upon the research that he has conducted pursuant to this ArcticNet grant over the past five years. Lackenbauer was appointed the Honorary Lieutenant Colonel of 1CRPG for a three-year term beginning in September 2014 based upon his research of and advocacy efforts for the Rangers. Accordingly, he will continue to have extensive opportunities to travel to Arctic communities to meet with Rangers and will continue to seek opportunities for emerging scholars (graduate students and postdoctoral fellows) to travel to the North for field research alongside or as part of Ranger exercises and other military or WoG operations.

Huebert continued to monitor and analyze contemporary Arctic security. In addition to presenting before the Canadian Standing Committee on National Defence, he gave eighteen different conferences across Canada, the United States, Spain, and China. He also published his research in a series of academic journals and made some of his conclusions more widely accessible by composing three editorials for the Globe and Mail. While his research continues to encompass the breadth of Arctic security issues, he focused on analyzing Canadian-American relations, exploring how Russian’s actions in Ukraine are complicating Arctic security, and advocating a combat capable Arctic Offshore Patrol Vessel design.

Lalonde’s activities over the past year included presentations to conferences in China, South Korea, and Iceland analyzing international legal developments in the Arctic and how these intersect with geopolitical and environmental security considerations. She also organized a panel on the “Future of Arctic Governance” involving emeritus Professor Donat Pharand as well as the launch of a volume in his honour (International Law and Politics of the Arctic Ocean: Essays in Honor of Donat Pharand) and a celebratory banquet within the context of the 2014 Annual ArcticNet meeting. She also organized a workshop at the Faculty of Law of the Université de Montréal on Arctic security with the participation of Dr. Nengye Liu, Marie Currie Fellow at the Law Faculty of the University of Dundee and ArcticNet network researchers from across various projects. Owing to her important research, Lalonde has been elected by the International Law Association Canadian Branch as the Canadian representative on the International Law Association Baselines Committee. Thanks in large part to ArcticNet’s generous support, she has also expanded her work into a new area of enquiry: the impact of existing international legal mechanisms in fostering environmental security in the Arctic. Her participation on two separate panels at the Second Arctic Circle Assembly speaks to her relevance and growing profile in the international dialogue and debate on this issue.

ArcticNet support also facilitated postdoctoral and graduate student research and conference travel in Canada, Europe, and Asia. For example, Ph.D. candidate Wilfrid Greaves was a visiting scholar at the Centre for Sámi Studies, University of Tromsø, Norway, from April-June 2014, and participated in the Institute for Advanced Sustainability Studies, Potsdam Summer School on "Arctic in the Anthropocene" in Potsdam, Germany, in June and July 2014. He also joined the research team on the "Human Security as a Promotional Tool for Societal Vulnerability in the Arctic" project through the University of Lapland, which is funded by Academy of Finland.

Dr. Heather Exner-Pirot's research this past year primarily focused on northern education and health care, but she has continued to research, write and present on issues of Arctic security, in particular related to Canadian foreign policy and the Canadian Arctic Council chairmanship. She continued to publish a geopolitics blog on Radio Canada's eye on the Arctic website and also published an op-ed in the Globe and Mail on Harper's Arctic policy. Furthermore, she continued as one of three editors of the Arctic Yearbook, an international and peer-reviewed volume that focuses on issues of regional governance, circumpolar relations, geopolitics and security. The Yearbook is an initiative of the Northern Research Forum (NRF) and University of the Arctic's joint Thematic Network on Geopolitics and Security.

SSHRC postdoctoral fellow (2014-16) Dr. Daniel Heidt continued to conduct archival research on the intersections of science, sovereignty, and security in the Cold War Arctic. He is in the process of completing the Joint Arctic Weather Stations monograph with Lackenbauer. In addition, he has developed his project management skills by working closely with Lackenbauer on strategic planning, budgeting, and reporting for this ArcticNet project. Travel support has facilitated his access to document and photographic collections at archives in Canada and the United States over the past year.

SSHRC postdoctoral fellow (2014-16) Dr. Adam Lajeunesse conducted three research trips to Yellowknife and one to Ottawa where he undertook documentary research and conducted interviews with CAF officers and other government officials on lessons learned from military exercises, Whole of Government interactions in the security domain, and oil and gas development in the Canadian Arctic from 1950 to the present (for a book that will examine the politics, economics, and local impacts of Arctic exploration and development within a global context).

Mitchell Patterson conducted interviews with Arctic scientists who work with the Canadian Rangers in collecting oceanographic data as part of his dissertation research. With the help of ArcticNet and NSTP funding, he also was able to travel to Yellowknife to collect primary documents from the 1st Canadian Rangers Patrol Group and completed preliminary archival work at the Canadian War Museum and the Directorate of History and Heritage in Ottawa. He has also acted as a research assistant for several publications concerning military operations in the Arctic and will contribute four chapters to a volume that he is co-editing with Lackenbauer on lessons learned from Canadian Ranger operations for the Canadian Forces Leadership Institute.

Lisa Beiler, an MA student in History at the University of Waterloo, conducted extensive research on Arctic survival techniques as part of research suggested and supported by Joint Task Force (North)/1st Canadian Ranger Patrol Group to produce an Arctic Survival manual for Canadian Rangers. This involved various research trips to Yellowknife and Whitehorse to meet with Rangers and Ranger instructors, as well as intensive work gathering and analyzing existing literature on Arctic survival (including military, civilian, and traditional knowledge perspectives). This project will continue based upon this important groundwork over the next year, with Ph.D. student Peter Kikkert assuming the role as co-project lead with Lackenbauer. After teaching for two years as an instructor at Aurora College in Fort Smith (2012-14), Kikkert focused his research energies over the past year on completing several book chapters and articles as well as on writing his dissertation, which he plans to defend this spring/summer.

Over this past year, various members of our research team have continued to refine our collaborative information gathering process. Students, postdoctoral fellows, and research assistants have continued to consult and digitize relevant archival document holdings in North America. For example, Heidt and Lajeunesse have conducted archival research on Arctic security issues in Ottawa (Library and Archives Canada, Department of National Defence), Winnipeg (Library and Archives Canada regional office), and Washington (National Archives and Records Administration), and Peter Kikkert in Yellowknife (Prince of Wales Northern Heritage Centre/NWT Archives). Lackenbauer and Heidt have also mentored graduate students and undergraduate research assistants in advanced archival research techniques, including use of finding aids, processing of digitized documents, and indexing. Furthermore, students and research assistants have also undertaken systematic research on Canadian and international newspaper coverage related to Arctic sovereignty and security issues. This material has been used in conference papers and public lectures, theses/dissertations, scholarly articles and books-in-progress, newspaper and magazine articles, and policy recommendations to government officials.

In May 2015, we have scheduled a two-day workshop on “Understanding Sovereignty and Security in the Circumpolar Arctic” to help bridge the gap between divergent understandings of security and sovereignty, and critically assess and contribute to academic debates around these issues in Canada and internationally. This gathering will involve 25-30 Arctic social scientists to present their current theoretical and empirical research, and to lay the groundwork for future analytical and policy work related to:

- the changing nature of “sovereignty,” security and safety challenges and opportunities in the Arctic region;
- the relationship between natural resource extraction (especially fossil fuels) and security, particularly for Northern communities and Arctic Indigenous peoples;
- the role of organizations such as the Arctic Council in coordinating regional inter-state relations and facilitating Arctic cooperation; and
- the security implications of emerging regional issues such as climate change, reduced sea-ice and increased maritime accessibility, and political disputes with Arctic neighbours (particularly Russia) for regional cooperation.

The workshop organizers (Lackenbauer and Greaves) anticipate that participants’ contributions will form the basis for an edited volume on “Understanding Sovereignty and Security in the Circumpolar Arctic” to be submitted in late 2015 for publication with a major Canadian university press. ArcticNet funding has been used to secure Greaves’s assistance in organizing the workshop, receive a Balsille School for International Affairs major workshop grant, and apply for a SSHRC Connection Grant (decision pending). Although the actual event will be held after the formal conclusion of this phase of ArcticNet, the network played a pivotal role in making the workshop possible.

Project Milestones:

- Edited manuscript (Lackenbauer) based upon Gordon W. Smith’s A Historical and Legal Study of Sovereignty in the Canadian North, 1870-1939 (University of Calgary Press, December 2014).
- Edited book (Lalonde and Ted McDorman). The Arctic Ocean: International Law and Politics, Essays in Honour of Donat Pharand (Boston: Martinus Nifjhoff / Brill, December 2014) (18 individual papers edited, including contributions from Lackenbauer and Kikkert and Lalonde).

- Book (Lackenbauer). Vigilans: An Illustrated History of 1 Canadian Ranger Patrol Group. Foreword by Rt. Hon. Stephen Harper. Yellowknife: 1 Canadian Ranger Patrol Group. 172 pp. Based upon the Lackenbauer's academic monograph (The Canadian Rangers: A Living History) and supplemented by additional research and photographs, this coffee-table style book was produced at the request of 1 CRPG to reach a broader public audience amongst Rangers and Northern Canadians more generally.
- Documents on Canadian Arctic Sovereignty and Security (series editors, Lackenbauer and Lajeunesse, managing editor Ryan Dean), supported by this ArcticNet project, the Centre for Foreign Policy and Federalism, and the Centre for Military and Strategic Studies:
  - Canadian Arctic Defence Policy: A Synthesis of Key Documents, 1970-2012 (Dean, Lackenbauer, Lajeunesse).
  - Legal Appraisals of Canada's Arctic Sovereignty: Key Documents, 1904-58 (Kikkert and Lackenbauer).
  - Lackenbauer and Lajeunesse founded this series in 2014 to disseminate collections of relevant, unpublished primary source material relate to Arctic sovereignty and security to assist academics, students, and policy makers. ArcticNet travel and research support has proven instrumental to the publication of the first two volumes, and has allowed members of the research team to collect material to produce the next three volumes on maritime sovereignty (Lajeunesse), the Advisory Committee on Northern Development (Heidt and Lackenbauer), and early Canadian Armed Forces expeditions in the Arctic in the 1920s (Lackenbauer) that are in production for publication in winter, spring, and summer 2015 respectively.
- Publication of policy briefs, background papers, articles and book chapters, as well as a book on Chinese interests in the Arctic and how these intersect with Canadian interests and priorities.
- Dissemination of research findings at Canadian and international conferences, workshops, government meetings, advisory boards, and stakeholder gatherings.
- Ongoing publication of scholarly articles and book chapters, as well as op-eds and shorter policy examinations for various working paper series, newspapers and magazines.
- Preparation of grant applications to continue ongoing work related to: Canadian-American Relations in the Cold War Arctic, 1946-72 (PI: Lackenbauer, SSHRC Insight grant); Preserving Circumpolar Cooperation, Preparing for Conflict: Russia and Canada in the North (PI: Huebert, SSHRC Insight grant); Building Experiential Learning Capacity in the Canadian and Circumpolar North (PI: Heather Nicol, SSHRC Partnership grant); Navigating Arctic Waters: The Polar Code and Beyond (PI: Kristin Bartenstein); Fulbright Arctic Initiative (Lackenbauer); and a Canadian High Arctic Research Station (CHARS) Science and Technology Program Letter of Intent (PIs: Lackenbauer and Brendan Griebel, Kitikmeot Heritage Society).

RESULTS

Throughout this ArcticNet phase, our research findings have indicated that rapid political, economic, social and ecological changes in the Arctic are fundamentally transforming regional security. Given the Arctic's particular history and its growing relevance to the security interests of both circumpolar and non-polar states, the issue of 'security' in the Arctic is a contested and evolving concept. Our team of historians, political scientists, international lawyers, and geographers adopt mixed qualitative methodologies to test social scientific hypotheses regarding the probability and potential forms of cooperation and conflict between and within Arctic states (particularly Canada) through trend analysis, historical and contemporary case studies, and dialogues with policymakers and community stakeholders.

Given the complexity and pace of Arctic change, the Department of National Defence's Arctic Integrating Concept notes that "new interpretive frameworks are essential in order to respond effectively to changes occurring in the region. Until these frameworks have been established, it may be difficult to understand what is happening in the Arctic, and provide options on how best to respond to crisis or emerging threats to Canadian security or sovereignty" (2010: 6). We seek to contribute to the development of innovative frameworks, both practical and theoretical, that are consistent with Canada's Northern Strategy and national interests. Accordingly, our results have important implications for academics, policy-makers, and Northern community members who benefit from more robust security and safety activities that capitalize on opportunities and address risks and threats in a culturally, and environmentally, appropriate manner.

International Dimension

According to Huebert (2014d), two major geopolitical trends are increasingly in conflict in the Arctic. The first is the "political and public effort (and hope) that the region can continue to develop as a zone of peace and cooperation build on principals of respect for Indigenous peoples and a commitment to sustainable development." Indeed, the leaders of Arctic states have publicly emphasized their desire to keep the region under a cooperative framework and abide by international law. They have furthered this aim by running joint military exercises, resolving longstanding disputes, and using the Arctic Council to negotiate cooperative treaties on subjects such as search and rescue. Despite these steps and aspirations, however, most Arctic states are procuring security instruments that exceed constabulary requirements. While Arctic states are modernizing their militaries and war-fighting capabilities, Huebert's research findings now indicate that conflict arising from these Arctic pressure points is unlikely – a significant departure from his earlier projections (Huebert 2001, 2003, 2005). Instead, he now emphasizes that outside developments, particularly political tensions arising from conflicts in other regions, could jeopardize Arctic cooperation.

Part of our project team's research over the past year analyzes the impact of the Ukrainian crisis on Canada's relations with Russia and the influence of these challenges on the circumpolar system. Our work has critically examined the potential consequences of a cooperation breakdown and suggests ways to mitigate damage to Canada's circumpolar interests. We also examine means of preserving a cooperative framework and insulating the region from the broader geo-political conflict, with due regard to political sensitivities and the idea of "Canada's principled foreign policy."

Russia's annexation of the Crimean Peninsula and its involvement in Eastern Ukraine has altered the status quo in Eastern Europe and in East-West relations generally – and has generated significant debate in Arctic circles. According to some Canadian commentators (including Prime Minister Stephen Harper and former Foreign Minister John Baird), some of the most direct and significant reverberations of Russia's apparent willingness to turn its back on international law and established international norms will be felt in the Arctic (Huebert 2014g). Despite media coverage which highlights intensified Arctic competition and frames Arctic challenges as seeds for potential conflict, Lackenbauer argues that policy over the past decade indicates a strong trend toward cooperation. Competition may exist, he notes, but this does not preclude cooperation in areas of common interest. Thus, although the Ukrainian crisis has spilled over into Canadian Arctic security rhetoric since March 2014, he suggests that this does not render obsolete the policy frameworks or underlying assumptions and logic that have guided Canada's integrated Arctic security strategy since 2009. The ultimate result of deteriorating Russian relations on Arctic affairs, therefore, remains to be determined.

Since the end of the Cold War, Canada has enjoyed the benefits of a cooperative international governance framework in the circumpolar Arctic (Young 2005). Issues of sovereignty and jurisdiction have been (or are currently being) worked out peacefully, scientific research was often undertaken jointly, and major issues were managed within the productive framework provided by the Arctic Council and other multilateral organizations (Roussel et al, 2012). Russia's actions in Ukraine, however, have revealed the potential fragility of these cooperative patterns, rooted in international law and multilateral institutions, that are built on a perception of national interest and states' willingness to cooperate. As soon as actors decide that it is no longer in their interests to pursue a cooperative approach, the system will begin to break down. Accordingly, Russian aggression in Ukraine and concomitant impacts on international relations are complicating Canada's circumpolar relationships. As Huebert notes (2014b: 5), Canada is struggling to balance "cooperating with Russia on Arctic policy while simultaneously harshly critiquing Russia over its actions in the Ukraine."

To date, Russia has sought to avoid the end of circumpolar Arctic cooperation. In late August, Foreign Minister Sergei Lavrov publically suggested that the Arctic region should be left outside of military rhetoric and that "it must not be made an arena for military contentions." With this statement, Lavrov was ironically addressing what he perceives as an increasingly militaristic tone from Canada (ITAR-TASS 2014). This desire to isolate the Arctic from other international development is directly related to Russia's immediate and pressing need to maintain an atmosphere of calm in the North, so as to safeguard its foreign investments and technology transfers from Western companies. Recent American, Canadian, and EU sanctions have begun to limit this investment, threatening Russia's principal motivation for Arctic cooperation – and posing a long-term, existential threat to the Russian state.

Russia also perceives NATO expansion as a threat to its national security. Over the past year, Russia has led Sweden and Finland to begin to reexamine NATO membership. Accordingly, these developments are complicating Canada's NATO relations. On the one hand, Canada has been one of the most vocal critics of Russia's actions in Ukraine, and has not shied from warning against similar action in the Arctic. In August 2014, for example, Prime Minister Stephen Harper highlighted the dangers of potential provocation or confrontation in the Arctic by suggesting that Canada must be ready to meet any Russian "incursions" in the region (Rennie 2014). On the other hand, Huebert observes, Canada has consistently opposed pressures from Norway and other NATO members to extend the defence organization's reach into the Arctic. Based on our research, Huebert, Lackenbauer, Lajeunesse, and Lalonde have been invited by the Department of Foreign Affairs, Trade and Development International Security Research and Outreach Programme (ISROP) program to debate ideas on how Canada can chart a responsible, constructive course vis-à-vis Russia that fits with Canada's "principled foreign policy" and upholds our national interests, as well as international stability and security within a circumpolar context.

Canada does not face strategic questions alone, and we work with our "premier partner" the United States to discern how best to view and respond to Russian actions. If both countries perceive the Russian aggression as a Ukraine-specific aberration that does not threaten *Arctic* security and cooperation, this will not disrupt the current policy framework. If one of the two countries deduce that Russian behaviour portends more general aggression and disrespect for international law, the reverberations may impact the alignment of Arctic policies and practices as well (Lackenbauer and Huebert 2014).

Both Canada and United States have developed extensive Arctic security policy frameworks that affirm the rising geopolitical profile of the region, reveal their assumptions and priorities, and indicate an evolution in how regional security is understood. Lackenbauer and Huebert's analysis (2014) of strategic documents produced by both countries since 2006 reveals that the two countries' evolving strategies and overarching national security objectives are well aligned, highlighting the advancement of security interests, pursuit of responsible stewardship, and strengthened international cooperation. Careful consideration of the core themes suggests that the Americans are developing an understanding of Arctic security that echoes much of Canada's thinking. Accordingly, they conclude that both Canada and the United States stand to benefit from leveraging investments that enhance existing relationships, given their long history of cooperation and shared interests in continental defence and Arctic security. Popular and public rhetoric often suggests that the region represents a major source of tension between the two close allies. This reflects Canada's persistent preoccupation with Arctic sovereignty, with the United States cast as a perennial threat since the days of the Alaska Boundary Dispute, as well as the United States' preoccupation with continental security since the Second World War. In practice, Canada and the United States have long collaborated in the Arctic through bilateral defence and security agreements, as well as in science and technology, environmental protection, infrastructure development, and surveillance. Canadian hypernationalism and the United States' global geopolitical interests often obscure this enduring partnership.

Detailed historical case studies by members of the research team confirm that Canadian and American interests were generally compatible during the Cold War. Friction was inevitable but manageable, and successful working relationships on diplomatic and military level explain how and why Canada's security and sovereignty interests were well managed over the last seven decades. Quiet diplomacy and practical, bilateral solutions allayed most of the acute "crises" concerns that arose. Accordingly, our research suggests that decision-makers today might seek to perpetuate a long tradition of cooperation with the United States that respects legal differences and seeks practical agreements without prejudicing either country's national or international interests.

More specifically, ArcticNet funding has allowed us to frame a research program that critically re-evaluates bilateral Arctic relations in the early Cold War through three book projects that will bring unique theories and fresh evidence to academic debates. The first book, co-authored by Lackenbauer and Ph.D. candidate Peter Kikkert, focuses on Canadian diplomatic and security policy-making from 1946-55. Building upon securitization theory and systematically analyzing archival sources, this book develops a theory of "sovereigntization" to explore how securitizing and sovereigntizing moves influenced the development of policy tools and instruments related to defence, diplomatic engagement, and international law. The second book, co-authored by SSHRC postdoctoral fellow Adam Lajeunesse and Lackenbauer, provides the first systematic analysis of U.S. naval task force activities in the Canadian North from 1946-60. These modern "exploratory" voyages charted new passages, yielded ground-breaking scientific information, and shaped logistic, transportation, and settlement patterns. They also led Canada and the US to collaborate and manage disagreements over Arctic sovereignty. The third book, co-authored by SSHRC postdoctoral fellow Daniel Heidt and Lackenbauer, critically interrogates the Canada-US Joint Arctic Weather Stations (JAWS) program that operated in the High Arctic from 1946-72. Drawing upon extensive archival evidence and interviews with former JAWS employees, this study goes beyond the diplomatic record and examines how technicians and maintenance personnel from both countries mediated Canadian-American relations on the ground. Together, these books transcend various scales to provide fresh insights into the history of Canada-US relations and the processes of defining and managing sovereignty and security threats.

Past relationships and experiences inform current expectations and future projections. Bilateral friction over sovereignty has never led to open conflict nor has it undermined defence cooperation to safeguard the Arctic and the North American continent more generally. Although neither Canada nor the United States predicts a near-term defence challenge in the region at present (see also Conley and Kraus 2010, O'Rourke 2014), both anticipate broader human and environmental security threats that require enhanced military capabilities (often in a supporting role to other departments and agencies). Coordinated planning will allow for both countries to invest in core Arctic capabilities specific to their national interests, while seeking complementarities – and avoiding unnecessary redundancies – in capabilities that relate to broader realities of continental defence. Both have identified gaps or seams that must be addressed, including Arctic Maritime Domain Awareness (MDA), information sharing, communications, and regional expertise to operate more effectively in the region (eg. USN 2014: 15). By operating and training together as participants or observers in national, binational or multinational exercises, the allies also leverage opportunities to improve knowledge, share lessons learned, build confidence, and prepare for future missions.

Recent examples suggest that enhanced bilateral cooperation is not only well entrenched but deepening. In December 2012, the commander of NORAD and USNORTHCOM and the commander of the Canadian Joint Operations Command signed the Canada-U.S. Tri-Command Arctic Cooperation Framework to promote enhanced military cooperation in the Arctic. "It strengthens an already unique and mature partnership where coordination and cooperation occurs on a regular basis," the document notes, emphasizing the importance of process to identify opportunities for further cooperation (NORAD 2012).

This past year, the research team also reframed Canadian Arctic security by contextualizing it within a broader maritime context. At a conference in Korea, Lalonde discussed practical arrangements that Canada and the United States have used to manage expectations and diffuse tensions in regards to non-Arctic maritime disagreements. Despite longstanding differences, the two states have always made reasonable accommodation to respect the other's perspective – particularly with regards to the Northwest Passage, where Canada has promoted and protected its ocean interests in ways that avoided provoking the US into taking directly or confrontational action. The American response to Canadian measures has been principally to protect its international legal position through protests and statements but not to engage in direct at-sea confrontation. By forming official and unofficial relationships, moreover, have these two Arctic neighbours have been able to devise mechanisms and arrangements to overcome significant differences and pursue collaborative initiatives.

Other team members have fleshed out historical aspects of the broader international context in which Arctic sovereignty and security fits. For example, Lackenbauer and Peter Kikkert (2014) explored the ramifications of Indonesia's attempts to draw straight baselines on Canada's legal approach to managing its Arctic interests. Rather than supporting or mirroring Indonesia's provocative international legal course, which would have precipitated strong American and Commonwealth opposition, Canada adopted a quiet, "gradualist" approach that benefited from Indonesia's legal trailblazing without disrupting Canada's core international relationships. More ambitiously, Kikkert's doctoral thesis titled *Grasping for the Ends of the Earth: The Evolution of Polar Sovereignty, 1900-1960*, contextualizes sovereignty and international law by historicizing it within a global history of sovereignty in the Arctic and Antarctic. His work provides insight into the complex interaction between state legal appraisals, national policy-making, and the evolving legal doctrine surrounding territorial acquisition. Kikkert's exploration of a convoluted legal landscape in which multiple versions of polar sovereignty often existed contemporaneously highlights the difficulties states had in determining the definition and function of sovereignty in the polar regions and in constructing state strategies that would effectively secure rights and claims.

Our team also interrogates outstanding legal questions today. For example, Lalonde's work on the specific rules governing transit by aircraft above an international strait (2015a) points to an issue of potential core relevance to Canada. She highlights the extent to which earlier discussions/debates centered around straits in which the international community had a vested interest, and those straits where substantial international use was clearly evident (including air routes). In terms of civil aviation, she observes, Canadian and international rules are similar. Accordingly, the issue comes down to the right to control access, particularly with regards to transits by military or state aircraft of a country's territory that is cut by an international strait.

New Arctic Actors

The globalization of Arctic affairs has led to a proliferation of non-Arctic state actors seeking a greater voice in circumpolar governance, precipitating a flurry of recent scholarly publications seeking to discern whether these actors pose a "threat" to Arctic state interests and security (Heininen and Nicol 2007, Wilson Rowe 2012, Lackenbauer and Manicom 2014). In particular, China's growing interest in the Arctic, coupled with its ever-growing wealth and military power, has generated alarm in Western circles. Journalists, policy experts, academics, and politicians have pointed to China as a potentially dangerous Arctic actor in a number of different forums, expressing anxiety over what this new interest may mean for Canada. Lajeunesse and Lackenbauer's chapter (2015) on China's mining interests in the North American Arctic assesses whether these interests constitute a threat to Canada and/or the circumpolar region as a whole. By examining patterns of Chinese investment and activities, they challenge the notion that Chinese state-owned companies are seeking to take advantage of Arctic countries as part of a 'long con' or serve as a 'Trojan horse' to augment Chinese political influence in the region.

Furthermore, Lackenbauer and Lajeunesse's co-authored book with James Manicom and ArcticNet investigator Frédéric Lasserre (2015) rebuts many alarmist narratives. Their introductory chapter sets up key debates around China's involvement in the Arctic. Chapter 2 sets China's Arctic ambitions in the context of debates over Chinese foreign policy and identifies a disconnect between the reaction to China's purported interests in the Arctic and its foreign policy tradition. It also explores the assumption that China is a revisionist territorial actor, motivated by resource concerns that could potentially dominate the Arctic Council. These notions contrast starkly with China's behaviour towards territorial and maritime disputes, its resource procurement strategy and its track record in international institutions, and its emerging perspective on Arctic governance. Chapter 3 critically examines Chinese scientific interests in the Arctic region, and concludes that Canada has little to fear from China as a growing contributor to polar science. Chapter 4 looks specifically at "Shipping and Sovereignty: Commercial and International Legal Dimensions of Interest to China." With the world's largest export economy, China is aware of both the global shifts that could be brought by year-round shipping and the effects this would have on global logistics patterns. Chapter 5 looks specifically at the question of Arctic resources and Chinese interests therein. Basing their analysis on Western reports, Chinese commentators anticipate that Arctic oil and gas will be important for the world economy in coming debates. Furthermore, China's seemingly insatiable demand for minerals from around the world will mean that, as Arctic resource deposits become more accessible, its interests will increase accordingly. China recognizes that the vast majority of Arctic resources fall under Arctic states' control. Nevertheless, given the capital-intensive nature of Arctic development, it is likely that China's financial resources will play a significant role in the form and pace of Arctic energy and mineral development over the next decade. Chapter 6 looks specifically at China's interests in the Arctic Council and the range of Chinese perspectives on Arctic governance more generally. In the end, our detailed study confirms the general findings of Jakobson and Jingchao (2012: 24), who anticipate that "pragmatic considerations will be the main drivers of China's Arctic policies" and that the Arctic is not likely to become a main priority in Chinese foreign policy over the next decade."

Domestic Dimension

A decade ago, debates over the Canadian Arctic revolved primarily around questions of sovereignty, with the metaphor of 'thinning ice' being deployed to illustrate the supposed challenges to Canada's Arctic claims (Huebert 2003). Consequently, the dominant Canadian Arctic security discourse fixated on questions of territorial sovereignty and international law to the exclusion of other potential security issues that accompany the ongoing concurrent transformations of the Arctic ecosystem and regional governance regime. Since 2009, official statements have emphasized that the Arctic sovereignty and security environment continues to evolve in a complex manner, with official messages about peace and stability in the region competing with political statements about the need to assert control over and defend areas within national jurisdiction(s). By clarifying historical relationships in the legal, defence, and security domains, and monitoring Arctic state announcements, government implementation strategies, media commentary, and academic debate on Arctic defence, security, and sovereignty issues, our project has produced new insights into geostrategic shifts in the circumpolar Arctic and how these impact Canadian interests. Furthermore, we have disseminated research results to various policy audiences to help inform Canadian decision-makers about major defence, security, and political trends. Through trend analysis, historical and contemporary case studies, and dialogues with policymakers and community stakeholders, team members have contributed to public debates about Arctic strategy, sovereignty, and security. Given the central place of Arctic sovereignty and security in the Canadian Government's Northern Strategy, our results reaffirm that assessing vulnerabilities as well as opportunities for enhanced security cooperation remains timely, relevant, and important to ensure positive interactions between national defence, security, and safety priorities.

Postdoctoral fellow Adam Lajeunesse's forthcoming UBC Press monograph, *Lock, Stock, and Icebergs* (2015), offers an in-depth summary and analysis of the history of Canada's Arctic maritime policy and the evolution of Canadian sovereignty over the Northwest Passage and the waters of the Arctic Archipelago. Canadian maps have long displayed border lines leading straight to the North Pole while politicians in Ottawa claimed that there was no doubt that the Arctic was Canadian. Behind the scenes, however, successive governments spent decades trying to figure out exactly which waters they were claiming, why they were claiming them, and how they could do so. Drawing on Canadian and American archives, Lajeunesse provides the first in-depth analysis of internal Canadian policy discussion in the 1950s to show the difficulties that the government had in determining the extent and the basis of Canada's sovereignty claim. It also offers the first look at secret high-level negotiations between Canadian and American diplomats in the 1960s, 1970s, and 1980s, when the two sides debated their positions on the law of the sea and Canada attempted to secure American recognition of its Arctic sovereignty. His close examination of these talks and the concurrent, internal Canadian policy discussion demonstrates how Canada's positions on the Arctic evolved to suit the country's broader international maritime and foreign policy goals. The book also offers an in-depth look at decades of American submarine activity in the Arctic and joint defence cooperation in Canadian waters. Using document collections declassified by the author, this work proves that this activity was cooperative and friendly – disproving popular assumptions that American submarine transits undermined Canadian sovereignty.

More specialized studies also clarified our understanding of evolving sovereignty and security environments. Lackenbauer, Kikkert and Lajeunesse (2015) produced an in-depth examination of Lester Pearson's history of Arctic diplomacy, concluding that, on the Arctic file, Pearson was decidedly 'unpearsonian.' Rather than pursue the quiet and realist diplomatic tactics for which he was known, Pearson's positions on the Arctic were poorly thought out and generally damaging to Canada's overall approach. Sheau Vong's M.A. thesis (2014) examined the influence of the construction of the Distant Early Warning (DEW) Line on Inuit life, with a specific focus on Inuit health care, vocational training, and social change. She challenged the simple narrative of the radar network as a revolutionary force, arguing that the sites affected Inuit life to varying degrees. She also critically examined federal government motivations, intentions, and execution of policies, revealing how the government's intentions were not always realized in practice and that how individuals involved in implementing policy played a significant role in shaping and defining development in the North.

Furthermore, our team launched the new, open-access, e-book series *Documents on Canadian Arctic Sovereignty and Security* to facilitate future research with robust historical grounding by providing scholars and policy-makers with easy access to primary materials that document Canada's policy history. The first volume, produced by Lajeunesse, Lackenbauer, and Dean (2014), provides a summary of and key quotations from major defence, foreign policy, and general policy documents and parliamentary reports covering Canadian security-related documents from 1970-2012. The second volume on *Legal Appraisals of Canada's Arctic Sovereignty: Key Documents, 1905-56*, edited by Kikkert and Lackenbauer (2014), offers historians, lawyers, and policy-makers with access to documents showing how Canadian, American and British legal experts attempted to untangle the complex sovereignty knot in the North American Arctic Archipelago in the twentieth century.

The Canadian Arctic Forces and Arctic Defence and Security

In May 2008, the Harper government released the *Canada First Defence Strategy* (DND 2008), providing a general policy framework that included several explicit references to the Arctic and emphasized the military's important role in "demonstrating a visible Canadian presence in this potentially resource rich region, and in helping other government agencies such as the Coast Guard respond to any threats that may arise." The following year, its Northern Strategy reaffirmed the broad array of military measures promised by the prime minister since he took office in January 2006 and assigned a robust role to the Canadian Armed Forces in the Arctic. This confirmation of early political messaging was now situated in an integrated, "whole of government" strategy, with the military playing an important but avowedly supporting role. These messages were reiterated in the government's Statement on *Canada's Arctic Foreign Policy*, released in August 2010, which confirmed a vision for the Arctic as "a stable, rules-based region with clearly defined boundaries, dynamic economic growth and trade, vibrant Northern communities, and healthy and productive ecosystems." Predictably, the first and foremost pillar of Canada's foreign policy was "the exercise of our sovereignty over the Far North" (DFAIT 2010: 5). Any concern regarding military security threats, however, was muted by an overall tone of cooperation with circumpolar neighbours. The document emphasizes that Canada "does not anticipate any military challenges in the arctic and believes that the region is well managed through existing institutions, particularly the Arctic Council" (DFAIT 2010: 3). It also insists that "Canada's Arctic sovereignty is long-standing, well established and based on historic title, founded in part on the presence of Inuit and other Indigenous peoples since time immemorial," and commits to resolve boundary issues in the region and to secure Canadian rights to the extended continental shelf in accordance with international law. "All disagreements are well managed, neither posing defence challenges for Canada nor diminishing Canada's ability to collaborate and cooperate with its Arctic neighbours" (DFAIT 2010: 24).

Strategic frameworks produced by the Department of National Defence (DND) and the CAF since 2010 reflect this commitment to work with circumpolar neighbours to ensure regional stability and security. Lackenbauer and Huebert (2014) observe that these documents share several core assumptions. First, they show a marked transition from a "use it or lose it" mentality, predicated on external security and sovereignty threats, to an explicit desire to seize opportunities for cooperation and collaboration with other Arctic states (particularly the United States) on matters of common interest. Second, they anticipate that climate change, and concomitant accessibility and global interest in Arctic resources and shipping routes, will generate economic opportunities but will also pose challenges for the environment and for the traditional lifestyles of Indigenous peoples. While strategic assessments do not perceive direct threats to Canada's defence and security at present, and do not anticipate any major changes to traditional roles of defending Canada and North America, they recognize the need for attentiveness to emerging "soft security" challenges. Thus, the focus is on "new" environmental, human and cultural security risks and less on traditional military security. The military is still considered to have a leading role in responding to Arctic emergencies, but it will "lead from behind", developing critical capabilities to counter threats within a Whole of Government approach and in partnership with international allies.

Our project has carefully monitored the Canadian military's Arctic initiatives over the past six years, critically interrogating perceptions of defence and security threats, Canada's military relationships with its Arctic neighbours, and the military's role in "exercising Canada's Sovereignty." Over the past year, for example, Huebert continued to chart developments in Canadian naval strategy (Huebert 2014c) and how plans for enhanced Arctic capabilities – particularly the Arctic Offshore Patrol Ships (AOPS), a new capability that will allow the Navy "to truly defend Canada as a *three* ocean state" (Huebert 2015). While Huebert concludes that these vessels may require a more robust combat capability to deal with emerging Arctic defence challenges, Lackenbauer (2014b) urges the government to deliver on promised investments aligned to Canada's Northern Strategy "before rashly ramping up to fight a fantastical Arctic combatant, conjured to the scene because of preconceived Cold War mentalities and international events unrelated to Arctic disputes."

In the end, both Huebert (2014f) and Ph.D. student Ryan Dean (2015) indicate that economic/budgetary pressures may inhibit the navy's plans to rebuild and modernize their Arctic capabilities in the coming years. Although the *Harry DeWolf*-class offshore patrol vessel acquisition project has recently been awarded an additional $400 million in funding, demonstrating the extent of the government's perseverance in implementing its Arctic strategy in the face of numerous funding constraints, Dean's paper situates this ship acquisition project within the larger defence budget and investigates some of the interrelated effects of these funding constraints on the AOPS program. He concludes that the compounding effects of inflation have been central to hollowing out the budget for these vessels, limiting the number and capabilities of ships that will eventually be delivered to the Royal Canadian Navy. This fits with broader international trends. As the 2013 DOD Arctic Strategy notes, investments in Arctic capabilities must compete with other domestic and international priorities for funding in an increasingly constrained fiscal environment. Despite the Harper government's strong commitment to enhanced Arctic defence and security, several expensive capital programs are still in the project definition or design phases. An economic downturn, abrupt shift in government priorities, or a change in leadership could jeopardize the implementation or sustainment of projects and capabilities upon which existing plans are predicated (Lackenbauer and Huebert 2014).

Our team has also worked diligently, in partnership with Joint Task Force (North) and Canadian Joint Operations Command, to launch a robust research program to document "lessons learned" from Arctic operations. Lajeunesse and Lackenbauer are co-editing a volume on Lessons Learned: *Sixty Years of CAF Arctic Operations* which includes sixteen chapters from leading experts and practitioners covering military operations from the Second World War to present. Furthermore, Lackenbauer, Kikkert, and Lajeunesse have partnered to research and write a short historical overview book of the Canadian Army's operational and tactical experiences in the North, and how its role was situated in successive governments' sovereignty agendas.

As Lackenbauer observes (2014b), the Canadian military's current strategic frameworks emphasize the security and safety aspects of the operations continuum, with practical guidance and planning focusing on better synchronizing the activities of the CAF, other government departments and the international community. They anticipate that climate change, resource development and melting sea ice will generate economic opportunities but will also pose challenges for the environment and for the traditional lifestyles of Indigenous peoples. While strategic assessments do not perceive direct threats to Canada's defence and security or anticipate any major changes to traditional defence roles, they are attentive to emerging 'soft' security challenges. Accordingly, they focus more on environmental, human and cultural security risks and less on traditional military security. Our research programme has both responded to and helped to shape these developments.

Broadening the Security Discourse

Ph.D. candidate Wilfrid Greaves' work explicitly argues that, in the context of transformative regional climate change, analyses that reduce Canadian Arctic security to Canadian Arctic *sovereignty* can no longer be sustained. Applying insights from the fields of International Security Studies and Critical Environmental Security, he concludes (2014a and 2014b) that the holistic nature of the Arctic environment and the scope of regional climate change require broader understandings of security that extend beyond traditional state- and sovereignty-centric interpretations to adopt conceptualizations of (in)security that operate above and below the level of the sovereign state and are better able to incorporate non-traditional security issues such as resource extraction, environmental degradation, cultural and linguistic survival, and ecosystem collapse. Failing to do so, he suggests, will produce major gaps and omissions in scholarly understandings of (in)security in the Canadian Arctic, and will contribute to the growing disconnect between scholarly discourse surrounding the Arctic and the reality of peoples' lived experiences of (in)security within and across the circumpolar region.

Energy is at the heart of some of the most challenging policy questions concerning the Arctic region, and several of our team members have engaged in theoretical and empirical research into the security implications of this issue. As climate change enables access to energy resources, many environmentalists and Indigenous peoples are increasingly concerned over the potential local and global ecological consequences of expanded hydrocarbon extraction. Greaves' paper at the 2015 Arctic Frontiers conference (2015b) examined this debate in terms of competing accounts of energy security versus human and environmental security in the Canadian Arctic, contrasting how energy and security are defined and understood by the Canadian state and by Inuit. By interrogating a range of primary and secondary research (including polling data, public documents, articles, speeches, interviews, and academic sources), his findings suggest that Inuit primarily articulate a conception of energy and Arctic security that that stands in opposition to that employed by the Canadian state. Whereas Canada sees hydrocarbon resources as contributing to energy security, Inuit tend to see them as further endangering the fragile Arctic ecosystem and indigenous ways of life. This raises important questions of how and by whom security is defined, and what role energy and hydrocarbon extraction play in understandings of who is to be made secure and through what means.

Other team members have pursued a different approach. Lajeunesse and Lackenbauer's short overview on "Developing the Offshore in the North American Arctic" (2014) seeks to dispel persistent myths, built up over the past decade, that resource development will ultimately provoke sovereignty challenges to Canada. They make the case for peaceful and orderly Arctic development, insisting that there is no need to fear an Arctic resource "race," and suggest how resource extraction will lead to more (not less) geopolitical stability in the region. Nevertheless, before the tempo of hydrocarbon development quickens in the North American offshore Arctic, several core issues will have to be addressed. Both Canada and the United States will have to clarify their environmental regulations, drilling requirements, and corporate liability laws. Indigenous concerns will have to be allayed and appropriate forms of participation worked out, and new infrastructure established to support safe and sustainable operations. In short, many hurdles remain to be overcome before the Beaufort and Chukchi seas are developed on a massive scale – but international conflict is not one of them.

Huebert, by contrast, highlights how exploratory drilling for oil off the northern coasts of Russia, the United States, Canada and Greenland could redraw the face of the entire region, arguing that opposition to oil development from environmental NGOs such as Greenpeace is "poised to become the most divisive issue facing the Arctic states in the coming years" (Huebert 2014a). He concludes that Canada must prepare to counter the inevitable protests that will follow any exploratory drilling in Canadian waters, and insists that it must have the capability to ensure order in the region once it has granted permission to companies to proceed with exploration.

Over the past decade, vigorous debate has taken place within academia and policy circles about the potential of Arctic shipping to heighten security risks and to undermine Canadian maritime sovereignty. Lackenbauer and Lajeunesse's policy paper (2014b) weighs in on that debate by analysing Arctic shipping patterns and prospects, as well as the political and economic incentives of shippers to either challenge or respect Canadian sovereignty. They project that future shipping will be destinational and not international in nature (eg. Lasserre and Pelletier 2011) and that this shipping will actually strengthen, rather than erode, Canadian sovereignty. Accordingly, the authors reason that Canada should focus more on practical issues such as mapping and infrastructure development to enable activity, rather than worrying about the higher-level sovereignty concerns that are well in-hand.

To reach a broader public audience, Lajeunesse and Lackenbauer published an op-ed in the *Globe and Mail* that appeared on 5 January 2014. This fit with a broader trend in that, given the political saliency of the subject of our project, team members have been frequently invited to share their views in the mass media. In addition to these contributions to the public debate, the research team is also actively tracking how the media has impacted Arctic security policy in the past. For example, postdoctoral fellow Mathieu Landriault's ArcticNet activities fit within his broader research agenda focusing on the influence of the media on political participation, perceptions and support. More specifically, he adopts discursive analysis to explain how the media mediate and popularize specific understandings of the circumpolar region, and how media commentaries frame the roles taken by civil society in the debate on Arctic security and sovereignty in Canada. His presentation to the 2014 Arctic Change conference shed light on how the Arctic security debate took form in Canada from 2000-2010, focusing on the editorial sections of 12 French and English newspapers. The type of threats perceived and solutions prescribed highlight how attempts at securitizing the Arctic can be counterproductive, overplaying fear and anxiety and influencing policy-making in sub-optimal directions.

While circumpolar states, the media, and non-Arctic commentators have primarily defined their changing 'security' needs in terms of economic opportunities and potential challenges to sovereign territory, Arctic Indigenous peoples usually define security in terms of the physical, socio-economic, and cultural impacts of environmental changes upon their lives and traditional ways of living (ITK 2013). Heather Exner-Pirot observes (2015b) that the "Arctic Paradox"—the irony that global warming related to the burning of fossil fuels will result in new sources of these fuels being extracted in the Arctic—has made the region one of the most important battlegrounds in the war against climate change. Although most people in the urban, industrial south view the Arctic through a lens of either climate change or economic opportunity, this overlooks the perspective of the peoples of the

North. For Northerners, the Arctic is not an abstract environmental object but rather a homeland, a workplace, and a community. Over the past four decades they have worked relentlessly to regain self-determination from national governments, she argues, only to once again feel marginalized by political actors in the mid-latitudes who claim the Arctic as their political, economic, and security domain.

Along similar lines, Will Greaves's dissertation research examines what security means to circumpolar Indigenous peoples and how their understandings of Arctic security link the changing natural environment to their physical safety and wellbeing, communal identities, and their rights to political autonomy and self-determination. His recent chapter (2015a) on "Environment, Identity, Autonomy: Inuit Perspectives on Arctic Security" undertakes a discursive analysis of the security claims articulated by Inuit organizations and leaders. First laying out how security is socially constructed and constituted through the shared understanding of particular sets of social actors, including Indigenous peoples, he then details Inuit understandings of security in the Canadian Arctic region. His data suggests that Inuit primarily identify referent objects of security within three categories: the natural environment, Indigenous identity and culture, and the maintenance of Inuit political autonomy. He concludes that Indigenous identity is a key analytical variable for explaining the exclusion of Inuit views within Canadian Arctic security discourse, and proposes an explanatory framework for the structural exclusion of the understandings of (in)security articulated by non-dominant groups from state security discourse. More generally, Greaves' work (2014d) highlights divergent and competing understandings of Arctic security. Whereas Inuit articulate a range of human security concerns related to the changing climate (ITK and ICC 2006, ICC 2008, ITK 2008), he argues that these differ from and ultimately contradict Canada's emphasis upon asserting its colonial Arctic sovereignty, extracting Arctic resources, particularly hydrocarbons, and avoiding climate change mitigation.

By contrast, Lackenbauer's work with the Canadian Rangers (2015a) points to aspects of convergence in security agendas. He concludes that the Rangers have a tremendous, constructive impact on the lives of people in their hamlets. From helping to recover lost persons to representing the military to setting a positive example for the youth, Rangers are always ready to participate. They are active community members who have a positive influence on their peers and are often seen as role models for young people. In turn, the Junior Canadian Rangers are the future leaders of the North and a key element to the sustainment of the Rangers. "The Rangers today are icons of Canadian sovereignty," Lackenbauer observes. "They contribute to domestic security, make important contributions to their communities, and are stewards of our northland. In an age of uncertainty, the Canadian Rangers in 1 CRPG remain vigilant: stalwart sentinels watching over their communities and the farthest reaches of our country." As Prime Minister Stephen Harper wrote in his foreword to Lackenbauer's forthcoming book (2015), "Canada's North is a land of exceptional beauty, boundless opportunity and great challenges. To thrive, our Arctic communities rely on a strong and abiding commitment to civic values of altruism and teamwork. No organization embodies these Northern attributes more outstandingly than the Canadian Rangers."

The Rangers are a critical component of the Canadian Armed Forces' efforts to improve their capacity to move, operate, and project power in the Far North. At the core of this drive is an operational framework known as 'Whole of Government' – a concept previously articulated as a "3-D" (defence-diplomacy-development) approach under Liberal governments (Lackenbauer 2009; Nossel 2011: 1-2). Strategic documents situate military roles in a pan-governmental context that assumes cooperation between the CAF and other government departments to achieve broader national objectives (CDS 2011). It is a simple idea but painfully difficult in practice.

Over the past year, Lackenbauer and Lajeunesse have begun a major project to analyze the Whole of Government (WoG) approach at the operational level using unpublished material and interviews with federal and territorial stakeholders. Their research identifies strengths, weaknesses, and opportunities for continued WoG cooperation between the Canadian military and other government departments. Their research findings suggest that efforts to create inter-departmental synergies to prepare, coordinate, and respond to practical security and safety challenges in a domestic Arctic context remain a work-in-progress. Despite the emphasis placed on Whole of Government in official policy statements, operations over the last decade reveal myriad barriers to effective integration and linking of government, local, and private sector partners. These obstacles include a lack of designated funding for initiatives that cut across departmental or government lines, policy structures that do not align (particularly across the civilian-military divide), and jurisdictional silos that inhibit (or prohibit) collaboration (Trent University et al 2014). Lackenbauer and Lajeunesse's initial article (2015c) on the subject frames a larger research program on how to envisage, implement and sustain comprehensive security approaches to ensure that they have direct, positive policy and practical benefits for governments and for Northern communities.

DISCUSSION

Since 2010, our team has pursued a vigorous research program. Interviews with dozens of government security officials from Canada and across the globe, archival and participant observation research facilitated the publication of more than 75 academic articles and book chapters, 3 major reports, 4 book-length monographs, 7 book-length edited collections, nearly 200 conference presentations, and 3 Ph.D. dissertations. Presentations to parliamentary committees, as well as professional development courses and lectures delivered to federal departments, demonstrate the policy salience of our ArcticNet-funded research. The project leaders' national profile as leading Arctic researchers, which has been enhanced by ArcticNet support, is substantiated by such honours as Huebert's role as a Canadian Polar Commissioner, Lackenbauer's appointment as the Honourary Lieutenant Colonel of the 1st Canadian Ranger Patrol Group based in Yellowknife with patrols throughout the Territories, and Lalonde's election as the Canadian representative on the the International Law Association Baselines Committee.

Our research on international geopolitical developments and the circumpolar system has had clear and important policy implications. Canada's Arctic policy has long pursued a cooperative international framework and it is in the national interest to uphold the governance structures that we have played a critical role in building up over the past three decades. Our research has yielded insights into how Canada can best insulate the Arctic from broader geopolitical tensions. For example, our research helps to inform policy-makers of the potential ramifications of increased Russian military posturing in the Arctic Basin or obstructionism at the Arctic Council. In the end, we anticipate that Canadian policy-makers will face challenges to maintain the decades-long trend towards enhanced circumpolar cooperation in the years ahead.

Anticipating what will unfold in a region changing as rapidly as the circumpolar north in the twenty-first century is difficult. "New interpretive frameworks are essential in order to respond effectively to changes occurring in the region," the Canadian Arctic Integrating Concept notes. "Until these frameworks have been established, it may be difficult to understand what is happening in the Arctic, and provide options on how best to respond to crisis or emerging threats" (2010: 6). A shared commitment to refining conceptual tools by continuing to monitor the Arctic security environment, the broader geostrategic situation, and the key drivers and assumptions framing policy development will allow the federal government and its partners at the local and international levels to mitigate risks, avoid unnecessary provocation (including on politically-sensitive issues), and share the burden of defending, upholding security, and promoting safety in the Canadian Arctic and the circumpolar North more broadly.

Given the multidimensional nature of emerging Arctic challenges, we hope that our articulation and adoption of broader definitions of Arctic security that move beyond potential inter-state military conflict to emphasize broader human and environmental issues will help to reorient scholarly research and the academic-policy interface. Priority security areas, which intersect with various ArcticNet projects, include search and rescue (SAR), major transportation disasters, environmental disasters, loss of essential services (e.g., potable water, power, and fuel supplies), organized crime, foreign state or non-state intelligence gathering activities, attacks on critical infrastructure, food security, and disruptions to local hunting and transportation practices caused by shipping or resource development.

The theoretical implications of our work also calls for a “democratization” of the security discourse. As Ph.D. candidate Will Greaves articulated to the International Studies Association meeting last year, the discursive logic widely advanced by the Copenhagen School’s securitization theory suggests that states – particularly democracies – should be responsive to security claims made by citizens. Despite this, circumpolar security policies have consistently failed to reflect the security claims of Northern peoples, instead (re)producing understandings of ‘Arctic security’ that exacerbate, or even accelerate, the insecurities identified by Indigenous peoples in the region. In the context of Arctic climate change, not only are Indigenous peoples experiencing environmentally-driven hazards to their lives, livelihoods, and traditional identities, but mainstream securitization theory provides an empirically and normatively unsatisfactory explanation as to why. His revised account of securitization theory seeks to explain the ongoing ‘insecurity of non-dominance’ of Arctic Indigenous peoples. First, it maps how ‘Arctic security’ has been conceptualized by organizations representing Indigenous peoples in the Arctic regions of Canada, Russia, and Norway. It then examines these securitizations in the distinct colonial-political contexts experienced by Indigenous peoples in these three circumpolar states. Finally, it seeks to explain this variation in indigenous Arctic securitizations, and their respective successes in their domestic political contexts, through a revised account of securitization that emphasizes two underdeveloped aspects of the Copenhagen School’s original theory: the historical constraints upon social constructions of domestic in/security, and the power relations that exist between identity holders.

Although most of the current debate over Arctic sovereignty and security anticipates the future, our research program also emphasizes how history continues to inform perceptions of Canada’s legal position, our sovereignty and security priorities, and relationships between the state, Northerners, and international stakeholders. Our work on the Cold War Arctic is *engaged* research because we connect it to contemporary issues without abandoning the primacy of historical context or forsaking the ideal of seeking to understand the past “on its own terms.” In our view, the challenge is to learn from history and inform better policies that balance domestic and international interests, justify appropriate and sustainable roles for the military and other instruments of the state, and reflect the priorities of Canadians. Our detailed historical studies raise core questions about the intersections of sovereignty, security, science, and technology in international and domestic contexts. How and why do various political, diplomatic, military, media, academic, and other actors perceive and construct threats? Does existing theory adequately explain *securitization* processes? How are security and sovereignty challenges managed in practice? How do modernist assumptions and inter-personal relationships facilitate or hinder the performance of sovereignty and security in isolated places? How did advancements in science and technology influence operations and perceptions of sovereignty and security? How are threat images diffused or translated to new (inter) national contexts?

ArcticNet funding has facilitated groundbreaking empirical research to test (and overwhelmingly support) our hypothesis that Canada and the United States have a long history of avoiding internecine battles over sovereignty by devising effective strategies to facilitate operational cooperation without undermining their respective legal positions. Our research program transcends various scales – from political and diplomatic offices in Washington and Ottawa, to the decks of US Coast Guard and Navy ships transiting Arctic waters, to the daily interactions of personnel at Arctic stations – to provide fresh insights into Canada-US relations and the processes of defining and managing sovereignty and security threats. We hope that our critical assessments of historical practices will help to frame and inform current decision-making, provoke continued dialogue and debate about Canada's Northern strategies, and yield new insights into how bilateral legal disagreements can be managed on an "agree to disagree" basis (Griffiths 2003; Lackenbauer and Huebert 2014).

The Government of Canada's 2010 *Statement on Canada's Arctic Foreign Policy* explained that "the United States is our premier partner in the Arctic." US Arctic policies also emphasize the "unique and enduring partnership" between the two countries in defence cooperation (US Navy Arctic Roadmap 2014: 7). This positive appraisal is warranted, despite scholarship that emphasizes bilateral friction and sovereignty disputes between the two allies. Based on the trends, predictions, and intentions identified in our research, we conclude that Canadian and American strategic frames and priorities for defence and security in the Arctic region are well aligned (Lackenbauer and Huebert 2014). The countries have a long history of cooperating to meet security threats in the Arctic and to North America more broadly. Working through existing defence relationships and institutions (such as NATO and NORAD), collaborating on threat assessments and in identifying gaps, and strengthening operational linkages will allow both countries to make complementary, targeted investments and leverage resources and capabilities to address shared needs.

Officials in both Ottawa and Washington recognize the advantages of collaboration and cooperation in light of their longstanding relationship, mutual interests in continental defence and circumpolar stability, and the high costs of developing and sustaining military capabilities in an evolving but uncertain security environment. Nevertheless, both states have other interests that complicate this effort. The United States is a superpower whose interests are global. Its perspectives on the Arctic are tempered by this reality. At the same time, Canadian officials recognize the necessity of cooperation but are bounded by a political and public sensitivity about Arctic sovereignty. The net benefits derived from collaborating and cooperating on areas of common interest, however, coupled with resource constraints and regional uncertainty, portend deeper cooperation in the defence and security domains.

Both countries acknowledge that the form, pace, and extent of future access to and human activity in the region remains highly uncertain. Both countries recognize that the region is undergoing a massive transformation, and that climate change and geopolitical developments are ending the region's isolation. Nonetheless, the complex array of variables at play makes it difficult to anticipate *what* activities are going to happen – and, equally important, *when* (Lackenbauer and Huebert, 2014). "The challenge is to balance the risk of having inadequate capabilities or insufficient capacity when required to operate in the region with the opportunity cost of making premature and/or unnecessary investments," the US Department of Defense's Arctic strategy notes (2013: 12). "Premature investment may reduce the availability of resources for other pressing priorities, particularly in a time of fiscal austerity." The political challenge of balancing official assessments that anticipate and seek to sustain regional peace and stability with popular expectations that the region is devolving into a zone of conflict (Wilson Rowe 2013) will remain difficult, particularly in Canada. While short-term defence requirements may remain modest, both countries have developed policy frameworks that will allow them to respond appropriately – and in partnership – if the region moves away from its established trajectory of international cooperation and stability.

The deterioration of Canada-Russia relations over the past year has served as a shock to circumpolar stability. If Russia decides that it is no longer in its interests to pursue a cooperative approach to Arctic development and governance, the cooperative system built since the 1990s will begin to break down. This could involve a non-functional Arctic Council, less search and rescue cooperation, increased military hostility and, potentially, a more unilateral Russian approach to continental shelf delineation. Furthermore, Russia may begin to express its displeasure with the West by using the North as a "posturing ground" where it could exercise its defiance of the West to maximum public effect, this in turn would only further damage relations and inhibit regional cooperation in the region more difficult. In response to the Ukrainian "civil war" which has exacerbated pre-existing fears of Russian military aggression, Canada has taken a strong political position vis-à-vis Russia that has spilled over into Arctic discourse. Canada has supported US and EU sanctions on Russia and is increasingly concerned about Russian flights into its Arctic Air Defence Identification Zone. Prime Minister Harper, committed to stopping Russian aggression, has warned Canadians that Russian President Vladimir Putin is "determined that, for Russia's neighbours, there shall be no peace," and "because Russia is also Canada's neighbour, we must not be complacent here at home." Does Russian aggression outside of the region and deteriorating relations with the West (particularly NATO member states) portend the collapse of decades of multilateral Arctic cooperation on issues as diverse as security, navigation, environmental preservation, jurisdictional limits, and scientific research?

While the framework for Arctic cooperation, developed over the past 25 years, remains largely intact it has begun to show signs of strain. Military cooperation has been reduced while strong political statements have been made at the expense of more practical, short-term interests (such as Canada's long list of objectives as chair of the Arctic Council from 2013-15). Our research team does not hold a consensus, however, on the implications for the Arctic security environment over the medium- to long-term. Suzanne Lalonde's comparative work (2015b) on Canadian and Russian approaches to sovereignty over the Northwest Passage and portions of the Northern Sea Route reminds us that sovereignty, in conferring vast powers and prerogatives, also involves reciprocal duties. By claiming sovereignty, Canada and Russia must act – and have acted – as responsible sovereigns, and this spirit is likely to animate both states' practical activities. Rob Huebert (2014d) warns that deteriorating relationships and future developments may undermine the Arctic security environment, given the non-linear transformation that has been disrupting traditional assumptions over the last decade. "This does not mean that conflict is inevitable," he suggests, "but rather that decision-makers in the Arctic region should not be complacent about the threats that they will be facing both from within the Arctic region and from outside." For his part, Whitney Lackenbauer (2014b) does not anticipate a major disruption of the existing system based upon current indicators. Recent "political statements, generated in a heated atmosphere in which Canada has taken a strident stand against Russian expansionism in Europe, may seem to support Huebert's argument that there will be conflict in the Arctic. After all, the geopolitical weather seems to be blowing in a worrying direction. But following short-term weather patterns is not a reliable measure of climate change. Long-term trends and sober analysis suggest that, even with the occasional cold snap, global warming is happening. Similarly, it takes more than political statements reacting to developments in Ukraine to demonstrate that the broader course of Arctic politics has shifted from cooperation and that, by extension, Canada should redirect its efforts to building combat capabilities in preparation for Arctic conflict." Lackenbauer argues that "regional priorities and threat assessments, used to frame Arctic defence and security frameworks over the last decade, remain sound. Accordingly, Canada's whole of government approach, designed to anticipate, prepare for, and respond to non-combat security and safety scenarios, should not be hijacked by a retreat to Cold War thinking." Accordingly, he concludes that "existing policy frameworks offer a realistic basis to respond to the most probable (non-military) short- and medium-term challenges that Canada is likely to face in the region. Rather than prematurely ramping up for an Arctic conflict that is unlikely to come, we should carefully monitor developments and wait for more sober indicators that the region is actually deviating from its established trajectory of international cooperation and stability before following Huebert's advice."

The Arctic has a central place in both the Canadian and Russian psyche and, in the event that Arctic cooperation collapsed, this could encourage Russia to use the region to demonstrate its defiance of the West with increased military action (such as strategic bomber flights or submarine voyages). There are no NATO military facilities or assets in the Arctic Ocean, so the chances of sparking a firefight between combat forces are slim to none – thus increasing the region's potential utility as a posturing ground to showcase Russian capabilities. On a political level, however, the fallout from such a breakdown would be significant (if less dramatic). Most importantly, the effective application of many of the rules established by the Law of the Sea Convention could be seriously impaired. For example, if Russia perceives that it has little to lose, it might opt to pursue a more unilateralist approach to delimiting its Arctic continental shelf. With the Commission on the Limits of the Continental Shelf unable to examine any submission where a maritime dispute exists (Article 5(a) of Annex 1 of its Rules of Procedure) and in light of the continued and likely long-term absence of the United States from the entire process, Russia – relying on the concept of inherent rights and the scientific data gathered by its scientists – might well decide to unilaterally fix the outer limits of its Arctic continental shelf, including along the disputed Lomonosov Ridge. The political repercussions for a Canadian government that has staked a great deal of political capital on charting and establishing sovereign rights to resources in that same area would be serious.

It is in Canada's national interest to prevent a serious breakdown in circumpolar cooperation and to ensure that the Arctic is not used as a military posturing ground. At the same time, Canada must continue to develop tools and capabilities to respond to potential challenges and threats. The conventional military threat to Canadian security remains remote, but complex and unconventional challenges remain, such as natural or human disasters, environmental degradation, increased search and rescue requirements, espionage, organized crime, and pandemics. Producing relevant, responsible, and realistic policy options to address these challenges requires a multidisciplinary, trans-sectoral approach. By effectively integrating and linking government, local, and private sector partners, solutions must seek to reconcile high-level political objectives with practical security threats, all the while rationalizing services and leveraging capabilities to avoid costly redundancies. An integrated, comprehensive approach is needed to compensate for the death of infrastructure and assets in the region, while ensuring a more focused response at an *operational* level.

Our project has developed tools and frameworks to discern best practices from Arctic operations, exercises, and relationships, as well as filling in knowledge gaps and identifying problem areas through in-depth case studies and interviews with Arctic practitioners and policy makers. Thanks to the foundation we have built with ArcticNet funding and networking opportunities, we intend to continue our work to produce innovative frameworks, both theoretical and practical, that build and refine comprehensive approaches to defence, security, and safety that are consistent with Canada's Northern and national interests. In turn, we hope that our research will continue to have important implications for academics, policy-makers, Arctic operators, and Northern community members, who will directly benefit from more robust security and safety activities that address their needs in a culturally and environmentally responsible manner.

CONCLUSION

Climate change. Newly accessible resources. New maritime routes. Unresolved boundary disputes. New investments in military capabilities to “defend” sovereignty. Unsurprisingly, the Arctic has emerged as a topic of tremendous hype (and deep-seated misperceptions) over the past decade, spawning persistent debates about whether the region’s future is likely to continue along cooperative lines or spiral into unbridled competition and conflict (Griffiths et al 2011). These debates about regional defence and security remain significant in shaping expectations for the Government of Canada and for the Canadian Armed Forces (CAF) more specifically. Despite the considerable ink spilled on boundary disputes and uncertainty surrounding the delineation of extended continental shelves in the Arctic, official statements by all of the Arctic states are quick to dispel the myth of a “race” between circumpolar nations, arming in preparation for a resource-fueled conflict (eg. Lackenbauer 2009; Lasserre et al 2013).

Our empirical research and meetings with senior federal, territorial, and military officials affirm the need for more academic attention to security issues (which are expected to proliferate as new development projects and trade routes emerge in the region) at the operational level. This requires a more nuanced and multifaceted definition of security than what typically has been a narrow, academic fixation on the possibility of inter-state conflict in the region (Nicol 2010; Lackenbauer 2013; Hoogensen Gjørv et al 2014). In the end, lasting solutions to complex security challenges (such as natural or human disasters, environmental dumping, increased search and rescue incidents, espionage, organized crime, or pandemics) require a system-wide, multifaceted response that integrates a wide range of civilian and military resources.

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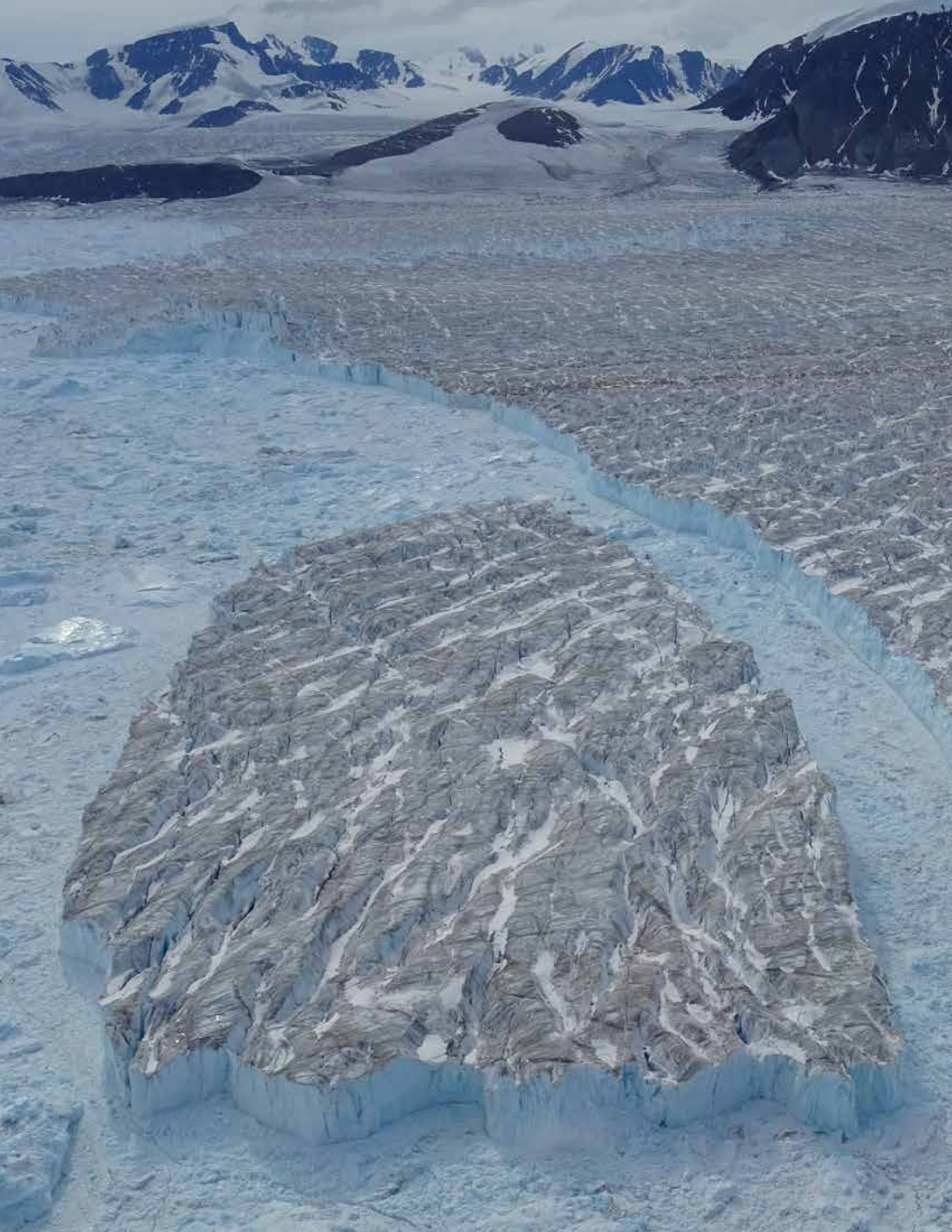

ADAPTATION, INDUSTRIAL DEVELOPMENT AND ARCTIC COMMUNITIES

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Exploring the closure of the Doris North gold mine and geographies of resource extraction in contemporary Nunavut
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ABSTRACT

Mining has become a complex and still poorly understood driver of both economic and socio-cultural change in the Eastern Arctic. This project has engaged in community-based, historical, and comparative research into industrial development as a driver of social, cultural and environmental change in the Canadian Arctic. In particular, researchers explored the cultural, economic and environmental impacts of past and present mineral exploration and development in several Arctic communities, including: Kugluktuk (Coppermine) in the Kitikmeot region, Qamani'tuaq (Baker Lake) and Kangiqiniq (Rankin Inlet) in the Kivalliq region, and Ikpiarjuk (Arctic Bay), site of the Nanisivik mine in the Qikiqtani Region. Research has also been conducted relating to the Polaris mine and the nearby community of Resolute. Working with community researchers and other collaborators, this project identified issues of importance in relation to mining development and community change, and explored community reactions and adaptations to the changes brought by industry. Researchers have collected extensive archival records relating to the history of industrial development in the Arctic, and will relate this history to changing government social and economic policies in the region, such as Inuit resettlement. Survey and ethnographic research in Arctic communities revealed a complex mixture of both positive and negative experiences with large-scale mineral development amongst Inuit. These impacts often have strongly gender-specific effects.

KEY MESSAGES

1. Historical encounters and ongoing legacies

- Historical industrial development has driven important social, economic and environmental changes in the Arctic, including changes to settlement patterns, community economies, and socio-cultural practices in Inuit and northern communities. Documentation of these experiences provides important context and lessons for contemporary Arctic development policy.
- Historical experiences of industrial development shape individual and community perceptions of and receptiveness to contemporary development proposals and activities. These perceptions may be positive (including a sense of identification with the post-mining landscape) or negative (including fears around social and cultural impacts, as well as pollution and environmental impacts).
- Legacy issues (environmental, social and economic) associated with northern resource development may persist long after the closure or cessation of resource extractive activities. In many cases, however, these issues are not well-documented or addressed in development policy.

2. Contemporary experiences and impacts of industrial development

- Inuit hiring, labour arrangements and work schedules at remote mine sites such as the Meadowbank mine pose particular challenges for Inuit workers. Key issues include: fly-in, fly-out labour arrangements; cultural accommodation and intercultural relations at the mine site; increased income and inequality in home communities; and employment and training opportunities. Many of these issues are gender-specific.
- Inuit traditional knowledge (Inuit Qaujimajatukgangit) can make important contributions for child care policy re-alignment and child welfare and protection policies, in the context of fly-in/fly-out work schedules for mine-involved families.
- Ongoing volatility and uncertainty in the mining sector indicates a need for economic, environmental and social development planning that accounts for the potential for mine shutdown and closure.

3. Mineral development policy and governance

- Institutional structures through which extraction is assessed and governed in Nunavut (such as the Nunavut Impact Review Board) have significant limitations in relation to knowledge production and dissemination, allocation of revenue streams, accounting for community concerns, and meeting the objectives of the Nunavut Land Claim Agreement.
- Impact-benefit agreements (IBAs) have become standard components of resource governance in the Canadian North. Currently, no public policy framework guides their negotiation, terms of reference, or implementation. Greater accountability and transparency is required in the negotiation and use of funds in relation to IBAs. At a time of accelerating mineral exploration and mine development in the North, it is important to critically interrogate the function, purpose, and effects of IBAs.
- The participation of Indigenous women in mining and the challenges this poses for the industry have received inadequate attention.
- The complexity and content of environmental impact statements (EIS) is a barrier to the participation of Inuit (and non-Inuit) community members in debates about environmental, social and the cultural implications of resource extraction projects in the Arctic.

OBJECTIVES

- To document Inuit knowledge, experiences and memories of socio-cultural and environmental changes associated with minerals-based industrial development.
- To study processes and impacts associated with past and present mineral development and resettlement in Arctic regions, including the effects of mine closure.
- To document the long term legacy issues associated with northern resource development and the controversies surrounding environmental remediation programs.
- To examine the historical and contemporary Inuit encounters with mineral development in the Kivalliq Region of Nunavut, including the Rankin Inlet nickel mine, the Meadowbank gold mine, and the proposed Meliadine gold and Kiggavik uranium mines.
- To determine the social and cultural impacts of resource extraction on women and families in the community of Qamani'tuaq (Baker Lake), Nunavut.
- To explore circumpolar comparative research and networking possibilities on the issues of extractive industries, community impacts and environmental legacies.

INTRODUCTION

Mining has become a complex and still poorly understood driver of both economic and socio-cultural change in the Eastern Arctic. From a low in the early-2000s (after the closure of Nunavut's two operating mines), the mining industry now constitutes a growing proportion of the territorial economy. From 2003 to 2011, Nunavut saw spending on mineral exploration and development increase six-fold. However, the recent decrease of global commodity prices has slowed the rate of exploration and development in the territory (NRCan, 2014a). As a result, between 2011 and 2014, mineral exploration and development expenditures decreased dramatically from $536 million to $148.1

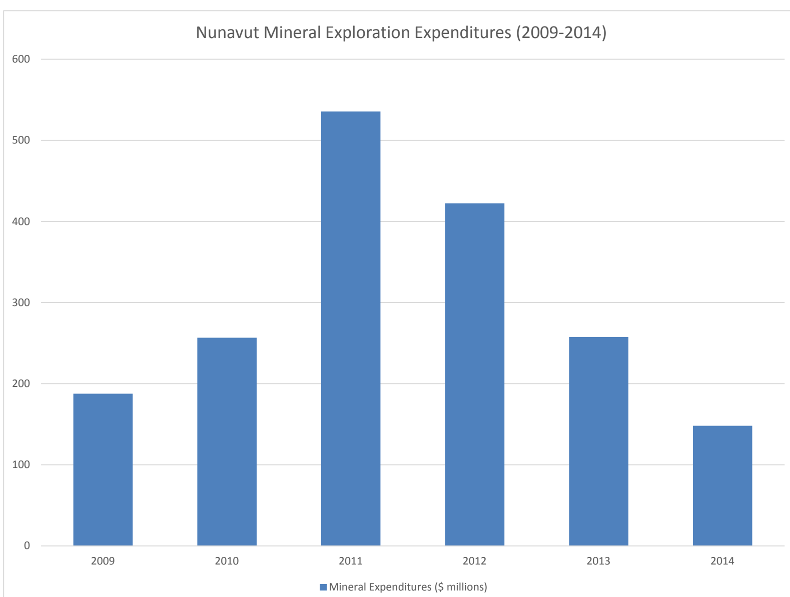

Figure 1. Mineral exploration and development expenditures in Nunavut (2009-2014). Data from NRCan, 2014b.

million (see Figure 1) (NRCan, 2014b). As of 2014, there were currently 47 on-going exploration projects in Nunavut, down from 140 in 2008 (NRCan, 2014b; Nunavut Overview, 2008). This period has also seen the suspension, curtailment, and even abandonment of mineral investments and developments in Nunavut.

Against this backdrop of the rapid expansion (yet extreme volatility) of mining investment, this project has undertaken community-based research into historical and contemporary Arctic industrial development. Through studies based on fieldwork in mining-affected communities, as well as documentary research into the legal and policy frameworks surrounding mineral development, our research team aimed to inform current debates and policy-making efforts surrounding the rapid industrialization of Arctic regions. The initial focus of this work was on three Nunavut communities currently encountering large-scale mineral exploration and development activities in their vicinities: Kugluktuk (Coppermine) in the Kitikmeot region, Qamani' tuaq (Baker Lake) and Kangiqiniq (Rankin Inlet) in the Kivalliq region. In addition, we extended our research to Arctic Bay (Ikpiarjuk), where we have examined the legacies of the former Strathcona Sound (Nanisivik) lead-zinc mine, and Resolute (Qausuittuq), the community closest to the former Polaris mine on Little Cornwallis Island. Preliminary research on the early exploration phase of the Baffinland iron mine on North Baffin Island was also undertaken.

This project explored how historical experiences with mining in Nunavut may inform contemporary reactions to and participation in new developments. This retrospective assessment of mineral development and closure provided insight into processes of Inuit adaptation to rapid socio-economic change (Tester et al. 2013; Keeling and Boulter 2015; Rodon et. al. 2013). These past encounters with mineral development left environmental, social and economic legacies that often persisted long after the closure or cessation of resource extractive activities (Keeling and Sandlos 2015; Midgley 2015; Cater and Keeling 2013).

In addition, our project examined aspects of the contemporary political economy of mining in Nunavut (as the territory grows increasingly dependent upon mineral revenues and employment), as well as community responses to and engagements in mineral project review processes. Institutional structures through which extraction is assessed and governed in Nunavut have significant limitations in relation to knowledge production and dissemination, allocation of revenue streams, accounting for community concerns, and meeting the objectives of the Nunavut Land Claim Agreement (Levitan and Cameron 2015). Important social challenges remain regarding Inuit hiring, labour arrangements and work schedules at remote mine sites, as well as the impact of fly-in, fly-out labour and the influx of wages and workers on communities. These impacts often have strongly gender-specific effects (Czyzewski et al. 2014).

ACTIVITIES

Research activities in the final year of the project focused on finalizing field activities, analysis and dissemination of results, as well as expanded networking activities:

1. Historical encounters and ongoing legacies

- Submission, revision and final delivery of peer-reviewed, edited volume, *Mining and Communities in Northern Canada: History, Politics and Memory*, to University of Calgary Press, for publication Fall 2015 (includes research results from ArcticNet projects and publication subvention from ArcticNet funding) (AK, JS).
- Presented "Aboriginal Communities, Traditional Knowledge, and the Environmental Legacies of Extractive Development in Canada," Arctic Change Conference, Ottawa, Dec. 11, 1014 (AK, JS).

- Editorial work on papers from the ArcticNet-sponsored 2013 workshop "Extractive Industries in the Arctic" for a projected special issue of the journal The Extractive Industries and Society (AK, JS Guest Editors).
- Preliminary assessment of archival sources related to MA student topic and decision to adopt the Mary River Mine (and not oil and gas exploration as originally proposed) as main focus for the MA project (JS, AK, RF).
- Research trip to Yellowknife to collect archival sources related to MA student Project on the history of the Mary River Mine (RF) [Note: student withdrew from program in December 2014 for personal reasons].
- Editing and production of film relating to the history of Rankin Inlet mine, based on research conducted for this project, including archival footage and contemporary interviews. (FT, AK, AF).

2. Contemporary experiences and impacts of industrial development

- Postdoctoral research into mine remediation practices in circumpolar north (AD)
- Participation in annual meeting of Knowledge Network on Network on Environmental Impact Assessment and Social Impacts of Mining the Canadian Eastern Arctic and Subarctic, Quebec City, October (AK, JC)
- Participation in workshop for Nordforsk grant application, "Resources, Extractive Industries and Sustainable Arctic Communities (REXSAC)," held in Stockholm, Sweden (AD, AK)
- Contributions to final Nordforsk Centre of Excellence application, "Resources, Extractive Industries and Sustainable Arctic Communities (REXSAC)," February 2015. This overall aim of the Nordic Centre of Excellence is to develop best practices on how extractive industries should be governed to ensure responsible/sustainable development, including through comparative circumpolar research. (AK, JS, AD)
- Data analysis of quantitative survey of the impact of the Agnico-Eagle Meadowbank Gold Mine on women and families co-ordinated by an Inuk researcher in Qamanit'uaq (FT, KC)
- Community workshop held in Qamanit'uaq, September 2014, to disseminate results of quantitative survey (FT, KC)
- Fieldwork in Arviat on the implications of fly-in/fly-out work schedules for mine-involved families in the community of Arviat. The research focuses on the implications for child care and child welfare within the context of Inuit families. It looks at the relevance of Inuit traditional knowledge (Inuit Qaujimajatukgangit) for child care policy re-alignment and child welfare and protection policies. (FT, PJ)

3. Mineral development policy and governance

- Detailed assessment of the ways in which Inuit Qaujimajatuqangit (IQ) was identified, documented, and synthesized in the assessment of the proposed Mary River iron ore mine in Nunavut, in order to critically interrogate the extent to which IQ shapes decision-making around mine development in the territory (AW, EC).
- Analysis of the ways in which key climate-related terms are translated into Inuktitut, investigating how notions of resilience, adaptation, and climate change itself mean something fundamentally different in Inuktitut than they do in English, with implications for climate policy and politics (EC, JM, RM)
- Review of policy and practice surrounding incorporation of Indigenous Knowledge (IK) and participation in regulatory review process surrounding mine remediation (JS, AK).

RESULTS

These activities have yielded concrete results, reported in previous reports, theses, presentations, posters, articles, and a forthcoming edited book (see "Publications"). We have also disseminated research results through formal and informal engagements with community groups, research partners, and Inuit organizations in the communities in which we have worked. The most recent results include:

1. Historical encounters and ongoing legacies

At Rankin Inlet, the development and the closure of the North Rankin Nickel Mine (NRNM) brought great changes to the Kivalliq region as a whole. This development was promoted by federal government officials as a key to the "modernization" of Inuit through sedentarization and wage labour (Keeling and Boulter 2015). A film project (working title: "The North Rankin Nickel Mine (1958-62): Modernization, Culture Change and Social Consequences") will document the experience, living conditions, social and cultural issues that arose at the time and the aftermath of this short-lived experience with industrial Canada. The film is being produced as a feature (60 minute) documentary using contemporary interviews with Inuit and non-Inuit who worked there as well as archival film footage and stills, as well as B-roll film shot in the contemporary community of Rankin Inlet.

Our research on mine closure and remediation suggests that scholars have been less inclined to address the long-term environmental legacies of large-scale developments, whether concluded or continuing, particularly the extent to which local knowledge and community perspectives are included in environmental remediation processes (Sandlos and Keeling 2015). Answering these questions will provide crucial insight into the ongoing environmental challenges associated with historic resource development, particularly extractive industries, and help guide decision-making in the future. In particular, there is a strong prospect for circumpolar, comparative research into the questions surrounding cumulative effects, long-term environmental hazards, remediation, and industrial heritage at Arctic industrial sites, past and present. Research and networking activities undertaken through ArcticNet have led directly to new research partnerships aimed at addressing this critical gap, including:

- collaboration within the Resources and Sustainable Development in the Arctic network (which, along with ArcticNet, cofounded postdoctoral research into these questions;
- participation in Knowledge Network on Network on Environmental Impact Assessment and Social Impacts of Mining the Canadian Eastern Arctic and Subarctic, which is also co-funding a student project along with ArcticNet;
- participation in a SSHRC Partnership Grant Letter of Intent application by Thierry Rodon to establish a Knowledge Network on Indigenous livelihoods and mining impacts in Canada, Scandinavia, and Melanesia; and
- participation in a Nordic "Nordforsk" grant application, "Resources, Extractive Industries and Sustainable Arctic Communities (REXSAC)," in collaboration with circumpolar scholars.

2. Contemporary experiences and impacts

Historical experiences with mineral development directly inform community perceptions and experiences of contemporary development. For instance, with the current growth in mineral development in the Kivalliq Region, experiences of the social and environmental legacies of the NRNM can and are being drawn on to better understand the risks and opportunities of contemporary developments such as the Meliadine mine. In particular, issues around adaptation to industrial labour (particularly fly-in, fly-out labour), responsibility for the environmental impacts of development, and the impacts of mine closure are at the forefront of contemporary community debates around mining in the Kivalliq (Cater 2013).

At Qamani'tuaq, qualitative research into the impacts of the Meadowbank mine on Inuit women revealed the intersectionality of impacts, involving combinations of: the two-week in, two week-out work schedule; increased income for those working at the mine; greater access to alcohol and drugs; and the occupational segregation of women (primarily housekeeping and kitchen work). The final report, The Impact of Resource Extraction on Inuit Women and Families in Qamani'tuaq, Nunavut Territory: A Qualitative Assessment, (Czyzewski et al. 2014) discusses increases in violence against women and children, the implications for the schooling of children of mine-involved families, sexual harassment and assaults against women, racism and discrimination in the workplace. The report notes that some families have benefited disproportionately from the presence of the mine, with implications for social harmony and relations in the community. It also identifies problems with the impact benefit agreement and its implementation.

Funding in the current fiscal year was used to complete and analyze the results of a quantitative survey co-ordinated by an Inuk researcher, Nadia Aaruaq, in the community. A group of Inuit women generated the content of this quantitative study as part of a previous week-long workshop conducted using popular education techniques. The workshop helped orient the women to different aspects of designing and conducting both qualitative and quantitative research. The results (n=60) have been analyzed using SPSS. A contract has been made with a recently graduated Master's student who worked with women in the community on the project. She is writing up the results in the form of a second volume report.

Of the participants who reported being employed, 11.7% were employed in the mining industry, working at the Meadowbank Mine, for AREVA (a French company developing a uranium mine to the west of Qamani'tuaq), or an exploration company. A further 30% indicated that they had worked for either Meadowbank or AREVA at some time in the past. Preliminary results from this survey indicate that individuals as well as the community are considerably divided and conflicted as to the benefits of mining for individuals and the community as a whole (Figures 2, 3). Taken together with other responses listing impacts, it appears that the community is better off materially – in that people have more disposable income, but that material benefits come with considerable social, psychological and cultural costs.

3. Mineral development policy and governance

Impact and benefit agreements (IBAs) have not been sufficiently theorized as they relate to processes of neoliberalization in Indigenous governance and resource governance in northern Canada. IBAs are functioning as tools for the privatization of the federal duty to consult Indigenous peoples about resource development on their lands, naturalizing market-based solutions to social suffering, and limiting access to important political and legal channels. (Cameron and Levitan 2015). As the example of the Meadowbank Mine illustrates, at a time of accelerating mineral exploration and mine development in the North, it is important to critically interrogate the function, purpose, and effects of IBAs.

Interpretation and translation between English and Inuktitut is a part of everyday life in Nunavut and is essential for ensuring informed, open, and meaningful public education, discussion, and decision-making. Translation has been a key site of conflict around

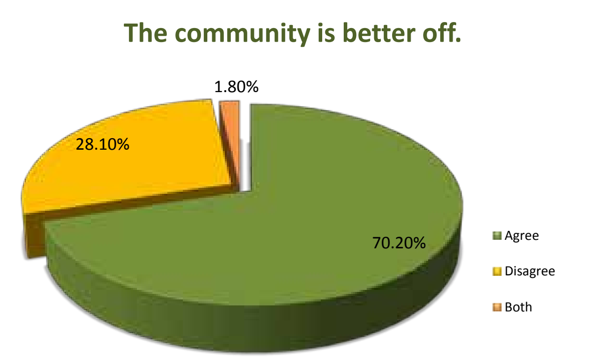

Figure 2. Survey responses to statement "the community is better off."

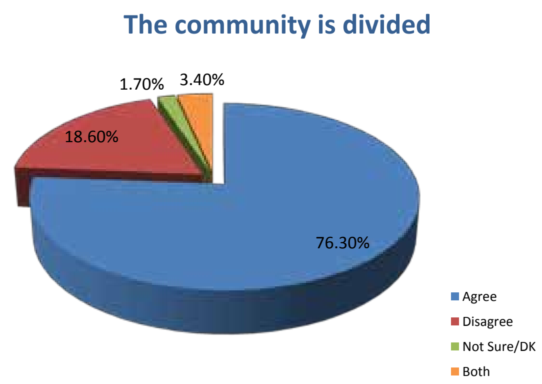

Figure 3. Survey responses to statement, "the community is divided."

the assessment of proposed mines in the territory; Nunavummiut have repeatedly expressed their concerns that important terminology around uranium mining is not adequately translated into Inuktitut, for example, and that key documents that are central to the assessment of proposed mines are not available in Inuktitut (Bernauer 2012).

Collaborative research into translation of key terms about climate change from English into Inuktitut reveals similar political implications (Cameron et al. 2014). Notions of resilience, adaptation, and climate change itself mean something fundamentally different in Inuktitut than English, and this has implications for climate policy and politics. To the extent that climate change is understood in Inuktitut as a wholly environmental phenomenon over which humans have no control, both "adaptation" and "resilience" come to be seen as appropriate and distinctly Inuit modes of relating to shifting climatic conditions, calling upon practices of patience, observation, creativity, forbearance, and discretion. If translated as a matter of unethical harm of sila, however, Inuit frameworks of justice, relationality, and healing would be activated. In the context of a broader global shift away from mitigation and toward enhancing the adaptive capacities and resilience of particular populations, current modes of translating climate change are deeply political.

Indigenous knowledge and participation in policy surrounding climate change and resource development are similarly problematic. Whether emphasizing its methodological, ontological, or epistemological merits, the "local" has become a privileged site for understanding and responding to climate change in the Arctic. But scale is not self-evident; it is a social and deeply political frame through which to understand any issue. The challenge facing critical scholars of Arctic climate change is therefore to unpack the intellectual and political implications of scaling Arctic climate change, and challenge the supremacy of an unquestioned "local" scale within which Arctic environments and peoples become legible (Cameron 2015).

Similarly, the incorporation of community knowledge and citizen participation in mine closure and remediation, particularly involving Indigenous people, represents a poorly understood aspect of extractive development. Because contamination and environmental remediation tend to be framed as technical issues beyond the scope of the public's understanding, the contributions of local and Indigenous people are often limited. In the case of mine remediation, we suggest that local Indigenous knowledge is often caught between complex technical discourses meant to address engineered solutions to environmental legacies and the practice of scoping out historic economic and environmental injustices deemed irrelevant to remediation processes that are meant to be solution-oriented, consensual, and apolitical (Sandlos and Keeling 2015).

DISCUSSION

Through this research, a complex, fine-grained picture is emerging of how Inuit people and institutions, individually and collectively, understand and respond to the changes associated with large-scale mineral development. Historical experiences with mining occurred in the context of a series of social, economic, and environmental changes, including relocation/

resettlement, the growth of colonial authority in the region, and shifting combinations of wage labour and subsistence practices (Tester et al. 2013; Keeling and Sandlos 2015). Similarly, contemporary mineral development is intersecting in complex ways with other developments in the Arctic, including Indigenous self-government and land claims, changing community and family arrangements, educational and technological change, public and private sector economies, and climate variability and change. Understanding how resource extraction intersects with and reinforces these challenges has been a key goal of the project.

Historical research is critical to understanding not only the social, environmental, and economic impacts of the development phase of resource exploitation, but also ongoing social and environmental legacies in the post-closure period. Our findings suggest that the question of how to remediate abandoned mines (or zombie mines [Sandlos and Keeling 2013]) raises many of the same controversies and environmental issues associated with the original development. New mines may similarly contribute to the cumulative effects of development in the vicinity of former mines. We have also begun to articulate how Indigenous knowledge and community interests might be incorporated into mine remediation processes, adding a social dimension to what are often highly technical processes. Our research suggests that contemporary assessments of mines and their impacts must account for these past experiences and understandings of work, its relation to traditional practices and knowledges, and relations with histories of colonization and dispossession in the Arctic (Sandlos and Keeling 2015).

Considerable social-scientific research effort is being focused on understanding the community impacts and benefits of contemporary mineral development (Ali 2003; Angell and Parkins 2011; Knotsch et. al. 2011). The picture of the social outcomes and changes initiated by large-scale developments and their associated IIBAs, however, remains far from clear, in spite of ongoing research into social indicators of development impacts (cf. Haley et. al. 2011). Community monitoring accompanying IIBAs, through bodies such as the Nunavut Regional Socio-economic Monitoring Committees, may provide useful information on short- and long-term changes to community conditions related to mineral development, as well as building capacity within northern communities to monitor environmental and social changes occurring over periods of rapid industrial development. Further attention is warranted to the signing and implementation of Impact and Benefit Agreements for projects with significant long-term social, political, economic, and environmental effects, and how these agreements may or may not effectively mitigate these effects.

Ethnographic research in Rankin Inlet and the community study in Qamani'tuaq using Participatory Action Research methods, both focused on the experiences of Kivalliqmiut with the Meadowbank gold mine, provide important models and insights in this regard. Contemporary mobile labour practices, particularly the two-week rotation schedule characteristic of remote mine work, pose challenges to the balance of family and work life for Kivalliqmiut. These stresses, as well as sometimes difficult intercultural interactions at the Meadowbank mine site, have led to high levels of turnover and personal stress among Inuit workers. In the study of Inuit women at Qamani'tuaq (Czyzewski and Tester 2014), key recommendations are made with respect to: women and an economic legacy; the provision of child care; dealing with addictions; greater support for families; mental health services; meeting the needs of youth; initiating lifeskills training and education; creating women and men's emergency shelters; and improving and introducing an effective program of cross-cultural understanding and historical awareness at the mine.

CONCLUSION

Industrial development based on extractive industries has become a cornerstone of federal and territorial economic policies for Nunavut. However, considerable volatility and uncertainty associated with this economic sector has recently been in evidence in the region: after a peak in activity in the early 2010s, forecasts indicate decreasing mineral exploration activity in Nunavut (Nunatsiaq News, 2015). Even the Qikiqtani and Kivalliq regions in Nunavut, areas that are particularly rich in gold, diamonds, silver, uranium, nickel, copper, platinum, iron, and oil deposits, are experiencing a reduction in prospecting and geological surveying, and there are few sites that are scheduled to go into production in the near future.

Notwithstanding these setbacks, it appears likely that a wave of industrial development will rise in Nunavut. Managing and better understanding these changes has become a central concern of territorial authorities, as witnessed by the extensive social impact assessment and monitoring procedures—and public debates—associated with major developments. These changes are likely to interact in complex ways with climate, socio-cultural, and environmental change in the region, and the cumulative impacts of these changes will test the resilience of already stressed Arctic communities. The encounter between small, geographically dispersed Inuit communities and national and transnational mining capital is of increasing interest to social scientists examining cultural and economic change in the Arctic (Bernauer, 2011; Cameron, 2012), and has been a central focus of this project.

Mineral development raises challenges for Inuit communities in particular, due to impacts on: food security and health; culture and language; rising income disparity; and family and social life (Gibson and Klinck, 2005; Angell and Parkins, 2011). Although many Inuit communities have found avenues for greater participation in the economic benefits of mining through Inuit Impact and Benefit Agreements (IIBAs), the pace of anticipated development underscores the need for appropriate governance and monitoring at the local, regional and territorial scales to ensure economic change does not undermine community adaptability and resilience (Bowman, 2011; Caine and Krogman, 2010). As critical drivers of environmental and social change in the contemporary Arctic, the mineral and energy industries pose major challenges to sustainability and the ability of communities to absorb and adapt to both the short-term impacts of development and its longer-term social and environmental consequences.

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SECTION V. KNOWLEDGE TRANSFER

Section V is composed of two ArcticNet research projects focussing on knowledge mobilization in support of sustainable development in the Canadian Arctic.

POLAR DATA MANAGEMENT FOR NORTHERN SCIENCE

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ABSTRACT

The progress of science towards interdisciplinary exchange and integration of information, such as in the ArcticNet Integrated Regional Impact Studies (IRISes), demonstrates the need for more efficient use of data resources using well-structured systems of data deposition and access. The central objective of ArcticNet's *Polar Data Management for Northern Science* is thus to facilitate exchange of information and data about the polar regions among researchers and other user groups, including northern communities and international programs. During Phase 1 of ArcticNet, members of Theme 2 initiated this data management project. ArcticNet then partnered with the Canadian Cryospheric Information Network (CCIN) at the University of Waterloo and the Department of Fisheries and Oceans Canada (DFO) to develop a database of metadata, the "meta-database" describing ArcticNet datasets. After several modifications and the joining of new partners such as the Canadian federal government program for International Polar Year (IPY), the Northern Contaminants Program (NCP), and Environment Canada, the ArcticNet meta-database, renamed the Polar Data Catalogue (PDC), was launched in July 2007. In 2010 the RADARSAT Polar Science Dataset was added to the collection, and in 2011 archiving and access to data files became functional. The Polar Data Catalogue is now Canada's primary on-line source for data and information on research in the polar regions. The scope of research covers a range of disciplines, from natural sciences to policy and health and social sciences. Research projects presented in the PDC are conducted under the auspices of a wide variety of programs, including ArcticNet, NCP, the Canadian IPY (2007-2008), the Circumpolar Biodiversity Monitoring Program (CBMP), the Beaufort Regional Environmental Assessment (BREA), and others. The Polar Data Management team is also working with other relevant projects (both national and international) toward integrated data management systems to ensure (1) preservation of polar metadata and datasets for the long term, (2) public accessibility of the metadata and datasets on the PDC in a timely and user-friendly format, and (3) responsive development of PDC data tools for use by various stakeholders, especially northern communities.

KEY MESSAGES

- The ArcticNet data policy and development of the Polar Data Catalogue (PDC) were initially motivated by the need for data sharing among ArcticNet researchers and with Northern stakeholders.
- The PDC team works on the continuous development of tools that will help researchers share and preserve their data and that will help users properly find, visualize, and use the data archived in the PDC.
- Each year, the focus on sharing data and proper data management increases in the international research community. 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. In 2013, the international Arctic Science Committee (IASC) released its Data Policy, stating that all IASC-endorsed projects require a formal data management plan including deposit in an archive and public access of the data files. In Canada, the Tri-Council released a draft digital scholarship policy framework for community consideration and response. The Polar Data Catalogue, co-developed by ArcticNet, the Canadian Cryospheric Information Network (CCIN) at the University of Waterloo, and many 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. Many new data files, particularly ArcticNet datasets from the CCGS *Amundsen*, have been added to the PDC and are now available for public access and download.
- In 2014, the PDC was approved as a member of the World Data System. In addition, an application for PDC to become the National Antarctic Data Centre for Canada has been submitted and is in the process of approval. These and other international linkages are increasing the global visibility of the PDC and ArcticNet data and science.
- The online PDC Search application has been updated, including addition of the 2008 RADARSAT-2 mosaics of the Antarctic continent which elicited responses worldwide and dramatically increased PDC web traffic for a month. Also, new data visualization tools were created for the CCIN website.
- The PDC Lite low-bandwidth search tool for northern use has been evaluated, and recommendations for improvement are being implemented. This Lite version of the PDC Search is better adapted to search for projects or information around a specific community, and it was developed in direct response to feedback and requests from northern stakeholders in ArcticNet.
- Significant progress has been made this year in sharing metadata with other polar data portals via internationally-standardized web services protocols. Metadata and data interoperability will continue to be a major focus of effort.
- The PDC and the Polar Data Management Committee have been actively expanding partnerships and collaborations at both the national and international level. Linkages across Canada and the polar world will help ensure access to ArcticNet datasets for the long term through the growing success and sustainability of the PDC.
- The PDC server and hardware configurations, Java application code, and data not duplicated outside the PDC archive are stored offsite for disaster recovery and protection against data loss.

The hardware configuration includes failsafe redundancy and continuous backup of data and software.

OBJECTIVES

The central objective of ArcticNet's *Polar Data Management for Northern Science*, as described in the ArcticNet Data Policy, is to facilitate exchange of information about the Canadian Arctic among researchers and other user groups including northern communities and international programs. To implement its Data Policy, ArcticNet was required to develop a system of information exchange among user groups and to create and maintain a database of metadata compatible with international standards. The creation of the ArcticNet metadata database and then of the Polar Data Catalogue has allowed ArcticNet to meet these objectives.

The specific objectives of data management for 2014-2015 have been:

- To work with ArcticNet and other relevant projects (both national and international) toward management of their programmatic data as well as establishment of integrated data management systems. In addition to ArcticNet, partners include the Beaufort Regional Environmental Assessment, the Northern Contaminants Program, Centre d'études nordiques (CEN), the Canadian Space Agency, Environment Canada and the Canadian Ice Service, the Global Cryosphere Watch of the World Meteorological Organization, the Canadian High Arctic Research Station, the Circumpolar Biodiversity Monitoring Program, Takuvik, the Canadian Polar Commission, Sustaining Arctic Observing Networks, and the Nunavut General Monitoring Plan.
- To ensure that polar metadata and datasets are preserved for the long term and are publicly accessible on the PDC in a timely and user-friendly format.
- To make links with other polar data organizations for sharing metadata through internationally-standardized metadata interoperability protocols.
- To rebuild the PDC Metadata and Data Input application using updated technology.
- To enhance the PDC and CCIN web portals by adding new data visualization tools and RADARSAT imagery.
- To archive the *Amundsen* data in the PDC.
- To assign Digital Object Identifiers (DOIs) to ArcticNet and IPY datasets.
- To make long-term plans for sustainability of the PDC, including planning for stable funding and options for replacement of the CCIN/PDC hardware and server infrastructure once it reaches end of life in a few more years.

INTRODUCTION

The Polar Data Catalogue (PDC, https://www.polardata.ca) is Canada's primary online source for data and information on research in the polar regions. Research projects presented in the Catalogue are conducted under the auspices of a wide variety of programs, including ArcticNet, the Northern Contaminants Program, the Arctic Council's Circumpolar Biodiversity Research Program (CBMP), the Government of Canada Program for the International Polar Year (IPY) 2007-2008, Environment Canada, the Beaufort Regional Environmental Assessment, the Nunavut General Monitoring Plan, the Canadian High Arctic Research Station, and others. The scope of research covers a range of disciplines, from natural sciences to policy and health and social sciences. RADARSAT-1 and RADARSAT-2 imagery from the Canadian Space Agency and the Canadian Ice Service of Environment

Canada are also available for viewing and download through the PDC.

The ArcticNet data management system was initiated during Phase 1 of ArcticNet by members of ArcticNet Theme 2 (*Food, Water and Resources in the Shifting North-South Thermal Gradient of the Terrestrial Eastern Canadian Arctic*), in response to the need to facilitate data access for collaboration and synthesis and to meet the information needs of ArcticNet Network Investigators (NIs), partners, and stakeholders (Vincent et al., 2010). To put in place this data management system, ArcticNet partnered with the Canadian Cryospheric Information Network (CCIN, at the University of Waterloo) and with the Department of Fisheries and Oceans Canada (DFO) to develop a "meta-database," a database of metadata records describing research projects and datasets. After numerous enhancements and updates, major development of online input and search engine tools by CCIN, and the addition of new partners, the ArcticNet meta-database, renamed the Polar Data Catalogue (PDC), was launched in July 2007. In 2010 the RADARSAT Polar Science Dataset from the Canadian Space Agency was added to the collection, and in 2011 the data archiving and access capability became functional. In 2012, the co-chairs of the Polar Data Management Committee were invited to participate in an Environment Canada Science and Technology Branch Northern Data Stewardship Workshop where the PDC was demonstrated as a model approach and success story to emulate.

The growing national and international profile of the PDC and the emphasis on data management by the ArcticNet international review panel underscores the quality of work of the ArcticNet and PDC data management team. This commitment is paralleled by the growing perception by government, funding agencies, publishers, and many scientists that data sharing and deposition should become a norm and a priority. This is particularly true now when advances in information technologies for gathering and accessing large volumes of data not only increase the 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). The progress of science towards interdisciplinary exchange and integration of information, such as in the ArcticNet Integrated Regional Impact Studies (IRISes), demonstrates the need for more efficient use of data resources using well-structured systems of data deposition and access. With its active participation in the PDC, ArcticNet is thus in a world-leading position for integrated data management systems and their ongoing advancement.

ACTIVITIES

Metadata and Data Management and Stewardship

All data management activities at the PDC support the goal of working with ArcticNet and other relevant national and international programs for long-term stewardship of their research and monitoring data, to facilitate scientific discovery through public access to data.

ArcticNet

Engagement with ArcticNet scientists and students has intensified this year, with 95 new metadata records and 50 new datasets being added this year, for a total of 763 total approved metadata and 84 total datasets, comprising 4,069 datafiles (further details are 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 the CTD and mooring data, to ensure their security and facilitate long-term archiving. The next steps are to create metadata records for the remaining *Amundsen* datasets and to complete the data organization and transfer to the PDC so that the data can be made publicly available, as appropriate. The

PDC Data Manager at CCIN in Waterloo, G. Alix, has assumed responsibility for review and approval of ArcticNet metadata and data submissions. In the coming year, we expect to increase focus on the large task of working with the ArcticNet community to prepare and submit their collected datasets to the PDC.

Other programs

PDC, which is a member of the Canadian Polar Data Network (CPDN, http://polardatanetwork.ca), is the chosen repository for the Beaufort Regional Environmental Assessment (BREA) program, the Northern Contaminants Program (NCP), the Nunavut General Monitoring Plan (NGMP), and the Canadian High Arctic Research Station (CHARS), programs within Aboriginal Affairs and Northern Development Canada (AANDC). In support of these programs, we inventory the datasets and work with researchers to create, upload, review, approve, archive, and serve online their metadata and data. The PDC Data Manager has written "project-level" metadata for each of the individual projects within BREA, NCP, and NGMP. With BREA coming to an end in 2015, significant efforts have been made to complete the BREA metadata and data collections. The PDC Data Manager attended the 2015 BREA Results Forum in Inuvik, NWT to present the PDC and meet with researchers to plan final submission of all BREA metadata and data files before the end of March. Further information on metadata and data statistics for BREA, NCP, and other partner programs are found in the *Results and Metadata* sections of this report.

To assist ArcticNet and our other partners, the PDC Data Manager makes numerous contacts with researchers, especially with respect to data preparation, submission, and review. For NCP, a special project is near completion to prepare the Yukon Contaminants Database for uploading to the PDC. Ms. Alix has also worked this year to add Inuit-specific keywords and locations to PDC metadata. She takes the opportunity when reviewing metadata records to ensure that names of northern locations include the name of the Inuit region, when applicable, and new keywords such as "Inuit Nunangat" are added to metadata when appropriate. Discussions are ongoing on options for ingesting data files from Inuit Tapiriit Kanatami (ITK) into the PDC. When time allows, Ms. Alix continues efforts to complete the metadata and data collections from the International Polar Year.

Work continues with the Circumpolar Biodiversity Monitoring Program (CBMP, of the Conservation of Arctic Flora and Fauna biodiversity working group of the Arctic Council) to create and enter metadata records in the PDC. We are finalizing an official agreement to formalize the relationship between the PDC and the CBMP Secretariat in Iceland. To complement the 194 metadata for the CBMP-Marine monitoring projects in the PDC, we have worked with Environment Canada and the Canadian Polar Commission on a project to complete the inventory for the CBMP-Terrestrial program, resulting in addition of over 300 new CBMP-Terrestrial metadata records for the PDC in spring 2015.

In our ongoing partnership with CHARS, we are developing a Data Policy in conjunction with their 2015 Call for Proposals. Drafts have been reviewed by a team of over one dozen professionals with experience in data management, including representatives from ITK and others with expertise in Traditional Knowledge and confidential data. We have also been working with CHARS to develop a Data Deposit Agreement for use with CHARS-funded researchers and a Data Access Agreement for use with non-CHARS-affiliated researchers working in and around Cambridge Bay. We anticipate also using the Data Deposit Agreement with NGMP researchers.

DOIs (Digital Object Identifiers) continue to be attributed to ArcticNet and IPY datasets archived in the PDC. DOIs not only provide greater access to datasets in the PDC but also provide benefits to researchers, including higher visibility of their data, enhanced opportunities for collaboration, and greater recognition via data citations. We are working on a new process to facilitate DOI assignment and entry of these metadata into the DataCite International online registration system. We anticipate completing this new process in 2015 and assigning DOIs for the 200+ datasets currently in the PDC.

PDC Online Application Development

The PDC landing page, https://www.polardata.ca (Figure 1) has been updated with new graphics, information on our metadata standards, and a more visible link to the PDC Lite application.

PDC Geospatial Search tool

The online PDC Search application has been updated with new enhancements and features (Figure 2), including addition of the Canadian Ice Service (CIS) sea ice chart collection, transformation of the PDC metadata to the ISO 19115 standard, integration of the 2008 RADARSAT-2 mosaics of Antarctica, and addition of new datasets, mostly from the BREA program, to the GIS Viewer. Conversion of the PDC metadata to ISO 19115 facilitates metadata interoperability with Canadian and international polar data repositories. In the PDC Search, PDC metadata are now available in the previously available FGDC standard (Federal Geographic Data Committee Content Standards for Digital Geospatial Metadata, FGDC-STD-001-1998) as well as the North American Profile of ISO 19115:2003 which is the Government of Canada's new standard for geospatial metadata.

The new CIS collection, made possible through the CanICE project of BREA, provides access to thousands of sea ice charts and observations from satellites and aerial and ship platforms, from 1993 to 2014. CIS continues to make enhancements to their database, thus we are undertaking further development to the PDC Search application to improve links to this database and increase the data and metadata available and viewable to our users. The PDC Data Manager presented the results of the CanICE project at the BREA Results Forum.

Integration of the 2008 RADARSAT-2 mosaics and associated higher-resolution tile products of the continent of Antarctica entailed modification of the PDC Search online tool to facilitate display and downloading of individual image files up to 10 GB. The release of this imagery was coordinated with the Canadian Space Agency and MacDonald, Dettwiler and Associates Ltd., the prime contractor for RADARSAT-2, and required blocking in our web configuration of access by 14 countries determined to be trade risks by the Department of Foreign Affairs, Trade and Development Canada.

PDC Metadata/Data Input tool

The PDC Web Developer, Y. Dong, is currently rebuilding the entire PDC Metadata and Data Input application using the latest web technologies and tools. This major upgrade will improve security, implement back-end improvements to the database to accommodate usage of a new web-database connection framework, modularize functions to streamline future development tasks, add a large number of new features, and optimize functions and database queries to provide faster searching and better performance for users. The code rewrite and cleanup represents the next step in adoption of new web technologies for the PDC and a reduction in time and effort required to respond to user needs and requests, maintain and enhance the applications, and train new co-op students and developers. The new design will incorporate the PDC glacier and logo into a simplified website design which is mobile-device enabled and has a modern look.

PDC Lite low-bandwidth search tool

The PDC Lite low-bandwidth search tool has been evaluated by staff at ITK, and recommendations for improvement are being implemented. To receive additional feedback, we are creating new surveys, to be reviewed for ethics compliance by the University of Waterloo, for the PDC Lite as well as the CCIN website, PDC Search, and PDC Input applications. We have compiled a list of northerners, researchers,

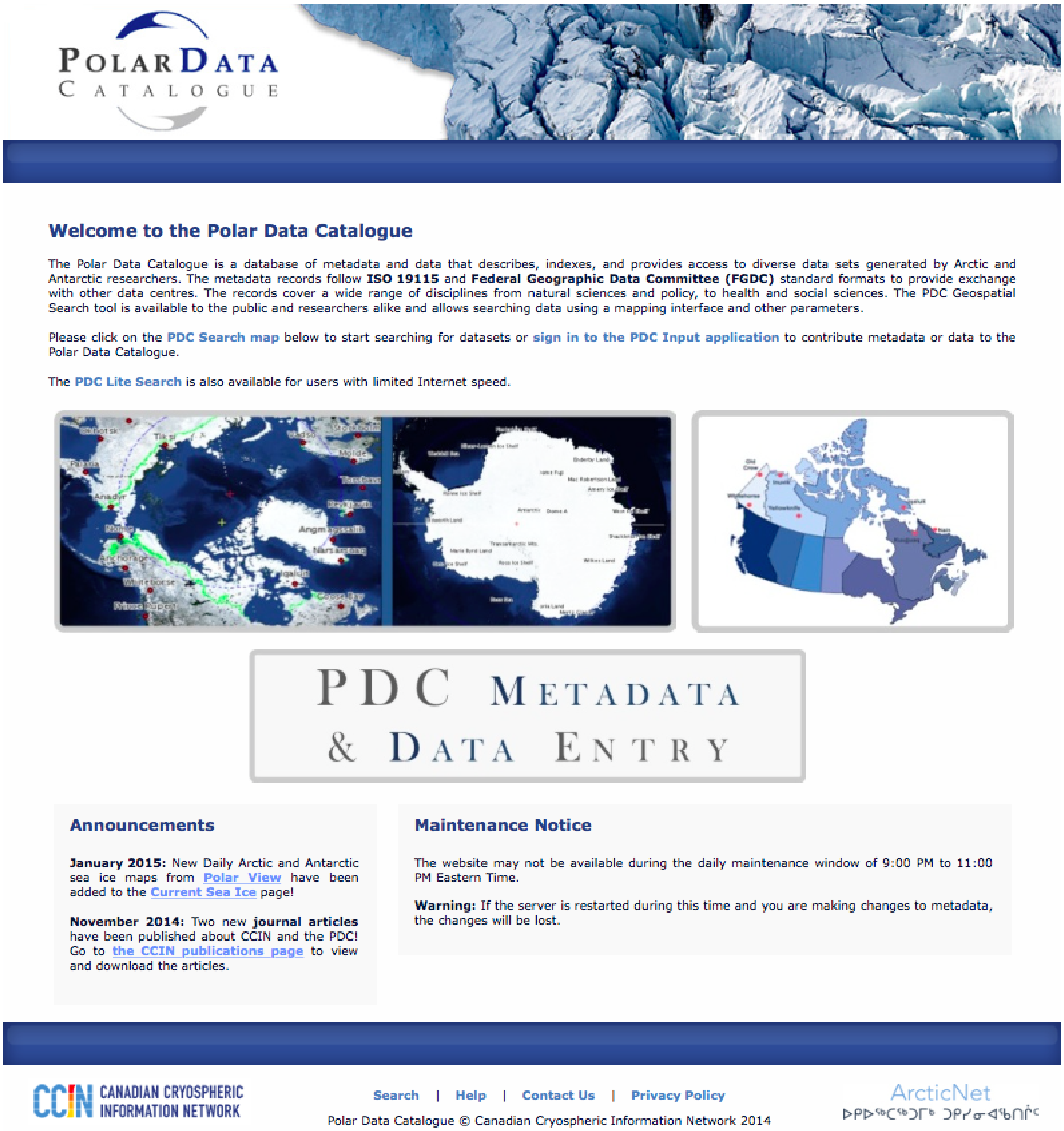

Figure 1. Polar Data Catalogue web site entry page.

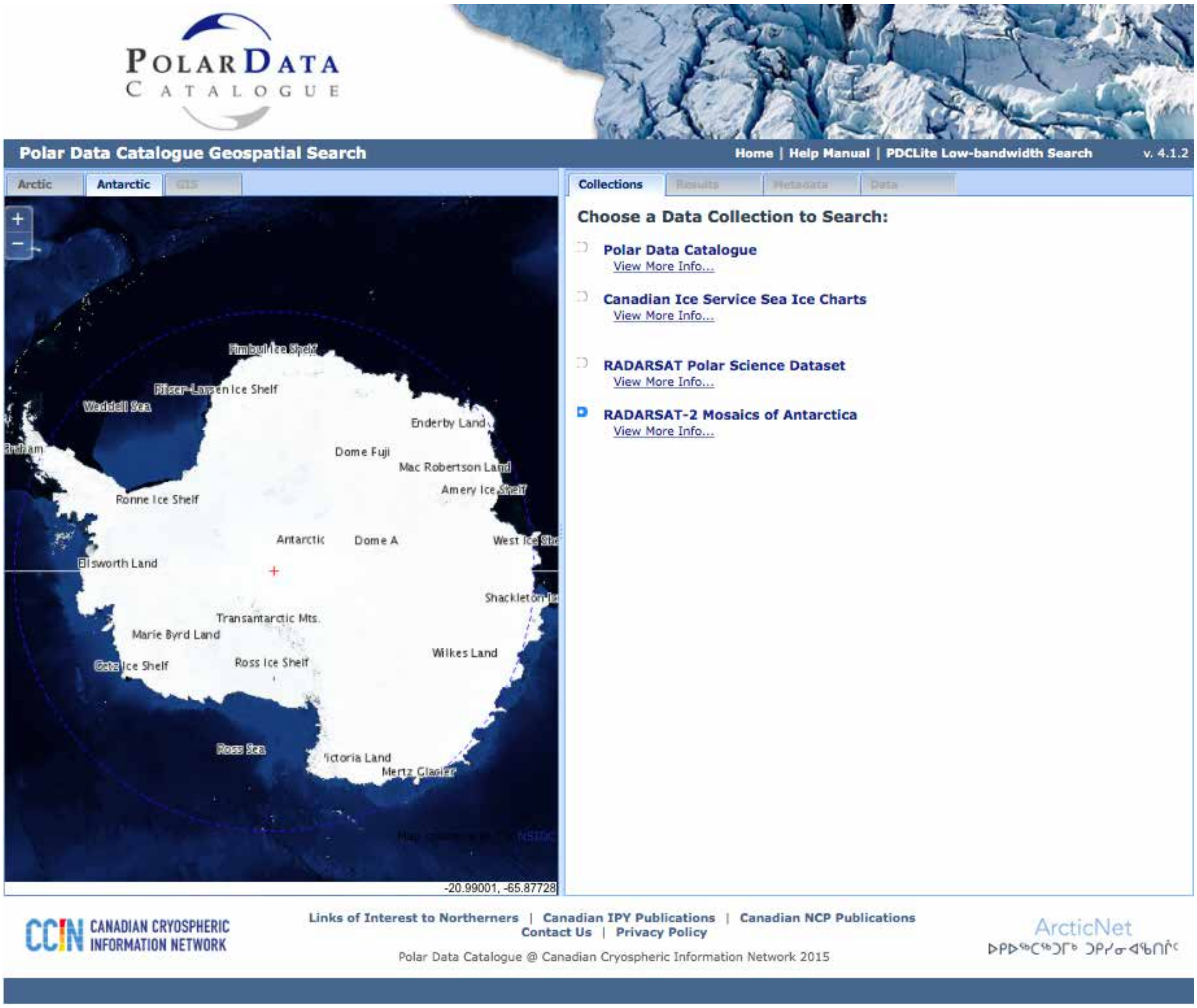

Figure 2. Polar Data Catalogue search application.

industry representatives, and other stakeholders to take the surveys in spring 2015.

In addition to improvements to the individual PDC online applications, an update to the PDC Help Manual is currently underway to incorporate Help documentation on the new features which have been added during the past year.

Interoperability with other Polar Data Portals

Metadata and data interoperability continues to be a significant focus of effort, with significant progress made in sharing metadata with other polar data portals. PDC metadata are provided for harvesting by other repositories via 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 the following organizations:

- National Snow and Ice Data Center, Boulder, Colorado, United States
- Polar Data Centre, National Institute for Polar Research, Tokyo, Japan
- Arctic Data Centre, Norwegian Meteorological Institute, Oslo, Norway
- British Antarctic Survey, Cambridge, United Kingdom
- Global Change Master Directory, National Aeronautics and Space Administration, United States
- Australian Antarctic Data Centre, Hobart, Australia
- Alaska Ocean Observing System, Circumpolar Biodiversity Monitoring Program, Anchorage, Alaska, United States
- Global Earth Observation System of Systems - Group on Earth Observations (GEOSS-GEO) Component and Service Registry, Fairfax, Virginia, United States

Work is advancing to make the metadata we harvest from these partners available in the PDC Search for access and discovery by our users. Contact to facilitate interoperable links has been initiated or continues with the following organizations:

- Yukon Research Centre, Whitehorse, Yukon
- ITK, Ottawa, Ontario
- Scholars Portal/Ontario Council of University Libraries, Toronto, Ontario
- Environment Canada, Downsview, Ontario
- Canadian government Open Data website, Treasury Board of Canada, Ottawa, Ontario
- Northwest Territories Discovery Portal/ Cumulative Impacts Monitoring Program, Yellowknife, NWT
- Environment Climate Data Sweden, Norrköping, Sweden
- Arctic Science and Technology Information System (ASTIS), University of Calgary, Alberta
- Arctic Data Explorer, National Snow and Ice Data Center, Boulder, Colorado, United States
- Ocean Tracking Network, Dalhousie University, Halifax, Nova Scotia
- Nordicana D, Centre d'études nordiques, Université Laval, Québec, Québec
- Ocean Biogeographic Information System (OBIS), Bedford Institute of Oceanography, Department of Fisheries and Oceans Canada, Dartmouth, Nova Scotia

Hardware, Infrastructure, and Security

In addition to the system and file redundancy that are in place on and near the campus of the University of Waterloo, progress has been made this year on establishing a full repository for backup of PDC and CCIN outside of the City of Waterloo. Discussions with SHARCNET, one of the Ontario components of Compute Canada, led to application for 40 TB of storage space to hold copies of all PDC and CCIN data, website code, database, operating systems and virtual machines, and configuration files. This proposal was successful, and in January 2015, we were awarded the storage space in another city in Ontario through the Compute Canada national Resource Allocation Competition. Work has begun to copy our files to this tertiary backup location. All data and files are encrypted before transfer to the remote server and are thus protected for privacy.

Other activities this year include a complete audit and cleanup of our Apache and other web configurations, addition of a new storage array to increase the data capacity of our production repository by 18 TB, application of an unusually large number of external bug fixes and security updates to our server infrastructure and web and database components (due to revelations from Edward Snowden and the resulting increased scrutiny of web-related software components and software), and long-term planning for sustainability of the PDC, including planning options for replacement of the CCIN/PDC hardware and server infrastructure once it reaches end of life in a few years. As a result of the Heartbleed security vulnerability that was found early in 2014, we made the decision to encrypt all of the PDC and CCIN web traffic and to run all of of our websites on https instead of http. This follows the decisions of many large enterprise systems, including Google and others, to encrypt all of their web traffic following the revelations of tracking and monitoring that have been in the news since summer 2013. These improvements are critical to ensure ongoing secure operation and to protect our users and the data that we hold for ArcticNet and our other partners.

The CCIN Systems Administrator, D. Friddell, conducted an energy audit, and we have arranged to offset our usage with green electricity from Bullfrog Power. The audit revealed that our total power draw (all office machines and servers/storage infrastructure) is approximately 1700 kW-hours/month, equivalent to approximately thirty 100W bulbs and less than that of a typical Canadian household.

Canadian Cryospheric Information Network website

The content and organization of the CCIN website have been further updated with the expert assistance of the Canadian Cryosphere Watch Scientific Advisory Council (https://www.ccin.ca/home/about/advisory), with significant new background information on cryospheric components (snow, ice, glaciers, etc.) and ecology added as well as new cryosphere-related scientific discoveries from the Canadian IPY program and the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Improvements have been made to the video section, large images have been reduced in size to optimize viewing on mobile devices, and all Flash video components have been removed from the site to enhance security for our users. The Kids section has been completely revitalized with new graphics, animations, and games, and the Frequently Asked Questions section has been expanded with many new questions.

Two new data visualizations have been added to replace the outdated snow-water-equivalent tools for the Canadian Prairies and the Northern Hemisphere (https://www.ccin.ca/home/ccw/snow/past/swe). These new interactive tools improve the user interface and provide more options for viewing the data in a graphical, map-based format. Work is in progress on a visualization of ice thickness data from northern Canada which will be completed in 2015.

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 the Antarctic mosaics which generated many re-tweets and forwarding of the information. On Twitter, we have 80 followers, and we have made over 1,500 tweets since creation of the account in 2011.

New Partnerships and Support

Our formal relationship with the Canadian Space Agency has been renewed via re-execution of the License Agreement until 2018. In addition, we have been working with a professor in the Department of Geography at the University of Waterloo to design and build a customized data management system for research data produced in her laboratory. A simple database and web front end have been designed and built, many datasets have been entered into the database, and a help and user manual has been written.

Potential new partnerships initiated this year include the new Arctic Science journal and the Québec Ministry of Sustainable Development, Environment and Climate Change, both of which have approached us about using the Polar Data Catalogue as their repository for data and metadata. Discussions are ongoing to work out long-term sustainable collaborations as a model for expanding relationships with an increasing variety and number of partners.

Proposals, pre-proposals, or letters of intent to support PDC and CCIN activities were prepared this year for existing and new partners at NCP, CHARS, CSA, GeoConnections, the Walter and Duncan Gordon Foundation, ArcticNet, Environment Canada, and Compute Canada. Proposals for new projects were initiated with the Belmont Forum (Supporting Global Sustainability through the Sharing of Arctic Observations and Research: Improving the Interoperability of Arctic Information, with the United States, Norway, China, Russian Federation, and Japan; we also provided a letter of support for a second Belmont proposal led by the Arctic Portal in Iceland) and the SSHRC Partnership Grant Insight and Connection program (Arctic Marine Use and Transportation Project (AMUT), a large Canadian consortium led by Jackie Dawson of the University of Ottawa). In addition, discussions are currently underway concerning PDC/CCIN involvement in a new cyberinfrastructure initiative from the Canadian Foundation for Innovation which may revive components from the 2013 NCE-Knowledge Mobilization proposal "ConnectNorth." The NCP, CHARS, ArcticNet, and Compute Canada proposals have been successful, and we await decisions from Environment Canada, SSHRC, and Belmont. In addition to these partners, ongoing support was received from BREA and NGMP.

Outreach, Communication, and Service

Local presentations by the CCIN Manager, J. Friddell, to the University of Waterloo community include a "lightning talk" and demo of the new Antarctic mosaic imagery at the University's GIS Day (November 2014), a presentation on *Sharing Polar Data at UW Using Web Services* at the University's annual WatITis IT conference (December 2014), presentation and discussions of *Best Practices in Data Management* to the Department of Geography's GEOG 600 seminar course in spatial data handling (February 2015), and a guest lecture, along with Y. Dong, on *Data Management for Geographic Science* to the Geography and Planning 387 course in Spatial Databases. In addition, *Arctic Change: Climate and Wildlife Changes in the Far North* was presented to the University of Waterloo's Unlimited Grade 10 High School Enrichment program (May 2014), the PDC was presented for a Canadian Ice Service/University of Waterloo Collaboration Workshop (June 2014), and the PDC and CCIN were showcased with G. Alix during International Education Week at the University (November 2014).

Due to the importance and value to the Canadian and international cryospheric research communities of the new Antarctic mosaics and tile images that were released on the PDC in August 2014, a press release was written by the University of Waterloo media office, and announcements were posted to scientific blog sites and the PDC's social media sites. As a result of the outreach, at least 22 news articles and reprints of the press release were posted online by newspapers and blog sites from around the world, and the PDC websites experienced a temporary 100-fold spike in traffic. In addition, the *Polar Times*, the magazine of the American Polar Society, highlighted the Antarctic imagery, specifically the Ellsworth Mountains, on the cover and back pages of its January 2015 issue.

To educate school children on the polar regions, J. Friddell engaged two elementary enrichment teachers in the Waterloo district to share information about Antarctica Day (1st of December). Grades 4 and 5 students viewed a presentation made by the international Antarctica Day coordinator in UK (http://www.ourspaces.org.uk/antarctica-day.html) and participated in an activity to design flags that would be printed out and taken to Antarctica with researchers, flown at the South Pole on Antarctica Day, and photographed for return to the students. Follow-up interaction to share information about a documentary

(*Cold Amazon*) and educational materials about the Mackenzie River and its effects on northern Canada has been initiated, with the teachers and an APECS outreach coordinator in London, Ontario expressing interest in showing the documentary in their classes and during Polar Week activities in March 2015.

Leonard Linklater interviewed J. Friddell for the CBC North Midday Cafe radio program about the PDC and changing weather in northern Canada (September 2014). Three articles (further information in the Publications section of this report) have been published in journals and proceedings volumes this year. Additional outreach and service include convening sessions on interoperability and stewardship of polar data archives at SciDataCon (New Delhi, India, November 2014), the Arctic Change conference (Ottawa, ON, December 2014), and, with P. Pulsifer of the Polar Data Management Committee, the Fourth International Symposium on Arctic Research (ISAR-4) and the Third International Conference on the Arctic Research Planning (ICARP III) at the Arctic Science Summit Week (Toyama, Japan, April 2015).

A new PDC/CCIN brochure which describes the PDC applications and the CCIN website was designed to take to conferences and meetings. It includes brief instructions on registering for the PDC Input tool and submitting metadata and data files.

Presentations were made at international and Canadian conferences as follows:

- Alix, G., BREA's Contribution to the Polar Data Catalogue. Oral presentation, BREA Results Forum, Inuvik, NWT (February 2015).
- Alix, G., The CanICE Project. Oral presentation, BREA Results Forum, Inuvik, NWT (February 2015).
- Friddell, J. and C. Elliott, The Polar Data Catalogue: Sharing Data for Science and the World. Plenary oral presentation, ArcticNet Student Association Student Day, Arctic Change Conference, Ottawa, ON (December 2014).
- Alix, G., C. Elliott, and J. Friddell, The Polar Data Catalogue: Data Management and Sharing Workshop. Two workshops to teach data management essentials during ArcticNet Student Association Student Day, Arctic Change Conference, Ottawa, ON (December 2014).
- Friddell, J., The Polar Catalogue - Update and Status for WDS. Poster presentation, World Data System members meeting, New Delhi, India (November 2014).
- Friddell, J., The Polar Data Catalogue: Sharing Data for Science and Society. Oral presentation, Ocean Networks Canada, Victoria, BC (September 2014).
- Friddell, J., Canadian Cryospheric Information Network and the Polar Data Catalogue: Data Management System. Oral presentation, Inuvialuit Settlement Region-Community Based Monitoring Program Data Management Workshop, Whitehorse, YT (PDC Manager was invited as an expert in data management to advise the ISR on establishing a database for themselves, September 2014).
- Friddell, J., The Polar Data Catalogue: Sharing and Archiving Canada's Polar Data. Oral presentation, Yukon Science Institute/Beringia Centre, Whitehorse, YT (September 2014).
- LeDrew, E., P. Pulsifer, and J. Friddell, Forming a National Antarctic Data Centre for Canada. Poster presentation, SCAR Open Science Conference, Auckland, New Zealand (August 2014).
- Friddell, J., The Polar Data Catalogue: Sharing and Archiving Canada's Polar Data. Oral presentation, MEOPAR Data Management workshop, Montréal, QC (March 2014).

In addition, J. Friddell, promoted to CCIN Associate Director in February 2015, has been invited to serve as a member of the Canadian Tri-Agency Data Management Policy Advisory Committee on behalf of the PDMC.

Polar Data Management Committee and other meetings

The Polar Data Management Committee (PDMC) held teleconferences in February, May, and September 2014 and had a face-to-face meeting at the Arctic Change conference in Ottawa, December 2014. Y. Crevier, Canadian Space Agency, and D. Scott, Canadian Polar Commission and Sustaining Arctic Observing Networks (SAON), joined the Committee, and C. Elliott was replaced by A. Stasko as the ArcticNet Student Association liaison. In addition, C. Gombault and G. Alix joined the PDMC by virtue of their new positions as data managers within ArcticNet and the PDC. P. Pulsifer and D. Hik continue to join our Committee meetings as observers. Finally, after many years of service to the PDC as Chair of the PDMC, W. Vincent stepped down and will be replaced on the Committee by C. Barnard. Dr. Vincent's energy, ideas, and connections have been highly valuable to the PDC over the years.

Following discussion with the PDMC, the PDC management has drafted a statement, approved by the Committee members for posting on the PDC website, to indicate that polardata.ca will be the sole web front-end for the Polar Data Catalogue. This policy has been considered by the PDMC in response to inquiries from partners on whether they could have their own branded web entry pages rather than the regular PDC front page. Committee sentiment was that the PDC has a unique and recognizable front-end web presence, and making a variety of new portal "faces" would be confusing to users and would also dilute the impact of the PDC.

In addition to other activities listed elsewhere in this report, PDMC tasks over the past year include public circulation of the Canadian Polar Data Network's 2013 data management report to CHARS, Committee consideration of a request for the PDC to join the Canadian Climate Forum (which grew out of the Canadian Foundation for Climate and Atmospheric Science), discussion with the Canadian Network of Northern Research Operators (CNNRO) about their data management needs and plans, consideration of a request from the CPDN for ArcticNet to consider use of the CPDN long-term preservation services, and connection to the Canadian Centre for Remote Sensing (CCRS, now CCMEO, the Canadian Centre for Mapping and Earth Observation). Advice and suggestions have been sought from the PDMC on how to work with researchers who will not improve their metadata when requested or who will not submit their metadata or data files.

Plans are in place to have C. Gombault visit the University of Waterloo during the summer of 2015, to work on data management for ArcticNet projects, particularly the *Amundsen* data, strategies for engaging ArcticNet researchers to facilitate ingest of datasets into the PDC, and enhancements to the PDC online applications.

Cost Model for PDC and the CCIN

With ArcticNet support, the CCIN engaged the MBA program at Wilfrid Laurier University in Waterloo, Ontario to develop a business plan and cost model for the PDC. WLU students participating in the Applied Business Research Project reviewed financial information from CCIN and provided an analysis of expenses which arrived at a "per Terabyte" cost for our operation under a variety of scenarios: (a) inside and (b) outside of the University system while considering current and projected costs (c) with and (d) without buying replacement servers and storage hardware in a few years. This analysis was an extremely useful snapshot of current and future costs, but it became apparent that conducting a full analysis which would provide numbers for use in pricing metadata, data, and other services to existing and new partners would require more extensive, and more experienced, consideration (described below). The other major deliverable of the WLU project, detailed in the final report, were recommendations to PDC and CCIN on forming and following a strategic plan for the future. Specific recommendations included focusing on ease of user interaction and looking for additional funding opportunities via providing value-added data and information to users for a fee. The team also conducted an extensive analysis of our web traffic and recommended using Google Adwords or equivalent advertising to reach a larger audience. We are investigating these options for implementation.

In working with the WLU team on creating a cost model for the PDC and CCIN, we identified the year-to-year basis of our funding as one of the main challenges to ensuring sustainability for the long term. It is difficult to forecast the funding we will be receiving in future years, and we can not carry over funds from one year to the next, a staple of long-term planning. This means that support provided this year technically only contributes to maintenance and improvement of the PDC and CCIN for one year, even though we are making commitments to our partners to hold their data “permanently.” This is not an issue with programs which will likely continue for the long term and have indicated their interest in partnering with and supporting us for many years, but it becomes a more difficult situation for short-term programs which have a limited lifetime. We need to ensure that the promise of long-term archiving and access made to our partners can be honoured. Accordingly, we need to understand the true cost of not only ingesting the metadata and data at the beginning but also the long-term costs of making sure the PDC repository and website are healthy for future decades. To help answer this question, we have engaged a local accounting firm to assess and quantify our multi-year cash flow and help us design and plan for sustainability into the future. The goal is to arrive at a complete pricing structure for the PDC’s core data management and related services which will facilitate creation of future funding proposals.

International Polar Data Management Activities and Strategic Planning

In September 2014, the PDC was approved as a member of the World Data System (WDS). This new membership, which required a significant and thorough application process and analysis of our systems and processes, validates the reliability, credibility, and security of the Polar Data Catalogue as a long-term data repository. As an obligation of this new membership, a PDC staff member is required to attend the WDS member forum every 2 years, starting at SciDataCon in New Delhi, India in November 2014.

The PDC has submitted an application to the Canadian Antarctic Research Program, affiliated with the Canadian Polar Commission, to become the National Antarctic Data Centre for Canada. Approval would oblige the PDC to hold all Antarctic-related metadata and data generated by Canadian researchers or projects and to share metadata with the the Antarctic Master Directory. A decision, and discussion on options for funding support of this new function, is expected in 2015.

J. Friddell was nominated as the Canadian representative to the International Arctic Science Committee (IASC) and SAON Arctic Data Committee (ADC), chaired by P. Pulsifer. The inaugural meeting of the ADC was held in Potsdam, Germany, in November 2014. On behalf of Canada, Dr. Friddell agreed to lead a project to determine the metadata “elements” (title, responsible parties, geographic location, etc.) which are critical to preservation and discovery of polar research datasets. This new activity will facilitate archiving as well as portal-to-portal metadata interoperability by defining the minimum amount of information that is necessary to reliably preserve polar data for the long term.

Dr. Friddell has been invited to serve as an international advisor on data management for Environment Climate Data Sweden. She will travel to Stockholm for the annual meeting of the ECDS Scientific Advisory Committee in March 2015.

The importance of data and its responsible management are increasingly being recognized by governments, the science community, and society, with Canada and other countries rapidly making changes to research policies to encourage and increasingly require scientists to properly manage their data. This changing landscape is attracting much attention among polar data managers who seek to contribute to good data management systems and practices. At the Scientific Committee on Antarctic Research's Standing Committee on Antarctic Data Management (SCAR/SC-ADM) in Auckland, New Zealand in August 2014, NI LeDrew, Dr. Pulsifer, and several other polar data managers proposed to hold an international polar data conference in Waterloo, Ontario. This conference, following on to the highly successful inaugural Polar Data Forum in Tokyo, Japan in October 2013, would be called *Polar Data Forum II: International Collaboration for Advancing Polar Data Access and Preservation*.

The Forum seeks to address priority themes and key challenges experienced by the polar data management community and to accelerate progress through clear actions to address the following target issues: (1) meeting the needs of society and science through promotion of open data and effective data stewardship, (2) establishing sharing and interoperability of data, (3) developing trusted data management systems and archives, and (4) ensuring long-term sustainable preservation of valuable Arctic and Antarctic data resources. The dates for the Forum are currently proposed for 27-29 October 2015, to be held in Waterloo in conjunction with the scheduled annual meetings of the IASC/SAON Arctic Data Committee and SCAR/SC-ADM, effectively creating a Polar Data Week. Planning is progressing, with first meetings of the International Advisory Committee (chaired by NI LeDrew and Dr. Pulsifer) and the Local Organizing Committee (chaired by Dr. Friddell) in February 2015, meeting space at the University of Waterloo reserved, and funding proposals to support local logistics in Waterloo and delegate travel underway.

Strategic Planning

The PDC and PDMC have been actively expanding partnerships and collaborations at both the national and international level, to ensure the success and sustainability of the PDC for the long term. Discussions have evolved into a letter to NSERC from PDMC Chair LeDrew and subsequently direct collaboration and meetings, in December 2014 and January 2015, with NSERC and SSHRC to coordinate data management for polar science in Canada. This effort involves planning for a Canada-wide dialogue on coordinating activities and systems, to culminate in a workshop in Ottawa in late spring 2015 led by the PDC and other stakeholders such as the Canadian Polar Commission and CHARS. This national planning is envisioned to lead into a strong Canadian contribution to the Polar Data Forum II later this year. Also included in the discussion is consideration of options for stable funding for the PDC and other polar data management activities in Canada, including funding and support to researchers in preparing and publishing their data. Our discussions to date have provided clear indication that the funding councils are supportive of our efforts to coordinate and advance data management efforts in Canada. They see the polar community as an excellent case study for building good systems and practices which can be emulated by others within and outside of Canada.

RESULTS

Metadata in the PDC

As of 22 February 2015, the number of metadata records in the PDC reached 2,009, with 6 in the SUBMITTED state, 4 in the SENT BACK state, 126 in the SAVED state, and 1,873 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 95 new metadata records, for a total of 763 approved metadata records.

Below is the inventory of metadata from our other partner programs:

- CEN: 67
- CBMP: 194
- IPY: 711
- CASES (Canadian Arctic Shelf Exchange Study): 78
- ADAPT (Arctic Development and Adaptation to Permafrost in Transition): 79
- NCP (AANDC): 91
- BREA (AANDC): 120
- APAN (Adaptation Program for Aboriginals and Northerners, AANDC): 113
- CHARS (AANDC): 8
- Reference: 70 (for other polar-related data and information portals and websites from around the world)

Also, we are planning to add 31 NGMP metadata. Fifteen project level metadata have been written for NGMP and will be finalized soon. These project-level metadata are high-level descriptions of each project and are linked to each of the individual metadata that have been submitted for each project ("dataset-level" metadata). Project level metadata have been created for 16 of the 23 BREA projects and numerous NCP projects. With the NGMP program staff, we are initiating the call for data for NGMP and expect submission of data files to begin in the coming months.

Number of Datasets

To date, 259 datasets have been submitted to the PDC archive, 84 of which are ArcticNet datasets. Fifty of these ArcticNet datasets have been added this year, for a total of 4,069 data files. Of all the archived data, 191 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 237,969 datafiles in the PDC overall, approximately 29 Terabytes in total, consisting of 17 TB of files from research datasets, 6.5 TB of RADARSAT imagery, and 5.5 TB of data files in our server that are waiting to be processed, reviewed, and approved before they are available on the PDC.

Traffic on the PDC and CCIN websites

PDC and CCIN website traffic is monitored via Google Analytics. Usage during January 2015 is as follows: 3,199 visits from 2,256 unique visitors, viewing 11,213 pages. This represents an increase over average monthly usage in past years, especially in the number of page views (~50% increase). As in past years, traffic generally increases in the winter, largely due to visitors to the CCIN website who are interested in snow and ice during the cold season as well as increased searching for data during the academic terms and increased submission of metadata during the winter and early spring funding reporting seasons. However, this year, there was a huge spike in traffic, up to 4,837 sessions in one day (20 August 2014), in association with the press release for the new Antarctic mosaics. The traffic remained high for several weeks and led to a large number of new users (26) and downloads of the Antarctic imagery (120) in a 3-week period.

Most visits to all four sites and applications (CCIN website, PDC Input tool, PDC Search tool, and PDC Lite) continued to be from Canada, but visitors also came from other countries such as the United States, United Kingdom, Hungary, Australia, India, Germany, the Netherlands, South Africa, and France. The most popular browsers this year are Chrome and Firefox, with Safari and Internet Explorer each having around 8% usage.

Outreach and Publications

In addition to the many presentations and published conference abstracts, three articles have been published this year which serve as important outreach materials for educating others on the functions of the PDC and CCIN.

DISCUSSION

The PDC continues to evolve into a reliable and recognized repository and access website for ArcticNet metadata and data as well as Canada's other Arctic and Antarctic data and information. Major accomplishments this year were a dramatic increase in the effort given to supporting researchers and focusing on entering metadata and data into the PDC, integrating the 2008 Antarctic RADARSAT-2 mosaic into the PDC and announcing the new collection to the world, and expansion of web services and linkages with other data portals for sharing the PDC metadata. Other specific activities include inventorying metadata and data holdings for our partner programs, adding new functionality in the PDC Search application, and improving the scientific and graphical content on the CCIN website.

Partnerships were established and strengthened with Canadian and international supporters and collaborators. Beyond the PDC, data management is rapidly becoming a formal requirement for research granting and coordination agencies around the world. The PDC is becoming much more involved in the international polar data management community through formal partnerships with IASC, SAON, the World Data System, and SCAR, the Scientific Committee for Antarctic Research. Through these collaborations, PDC staff are learning more about international trends in data management which can be implemented for improvement to our system and processes.

Over the past few months, we have heard from researchers who indicate that they are planning to use the PDC for all of their data management in the future, beyond their obligations for specific programs which engage us for data management activities. They plan to write this into their proposals and expect to have the PDC available to support themselves and their students for management of their research data collections. This signifies a maturity of the PDC platform and presence in the minds of scientists in the Canadian cryospheric research community to the point that they expect the PDC to be available to them for the long term. We need to engage with these and other researchers (as well as the federal scientific funding agencies) to work on a sustainable model for support for Arctic and Antarctic data stewardship in Canada. The Polar Data Catalogue, co-developed by ArcticNet, CCIN, and many other contributing partners, prepares ArcticNet researchers and places them at the forefront of the evolving data management requirements and expectations of the Canadian research community.

CONCLUSION

Continued development of the PDC is strengthening effective management of polar data in Canada. 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. 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. 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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We are grateful to the Polar Data Management Committee members who have worked diligently this year to guide the PDC team, particularly with respect to our long-term sustainability. We would like to recognize Keith Lévesque, Marie-Ève Garneau, Colline Gombault, and Gabrielle Alix who conducted the reorganization and entry of the *Amundsen* datasets and other ArcticNet data into the PDC. We would also like to thank Warwick Vincent for his many years of contributions to the PDC and the Polar Data Management Committee. This project was funded by ArcticNet, Aboriginal Affairs and Northern Development Canada, Environment Canada, the Canadian Space Agency, and the Canadian Polar Commission.

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ENABLING THE COPRODUCTION OF INUIT AND SCIENCE KNOWLEDGE THROUGH INTEGRATED INFORMATION MANAGEMENT

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ABSTRACT

There is a growing need for knowledge sharing and coproduction among Inuit and Northern researchers as the Arctic continues to experience rapid and unprecedented changes and there is a plethora of new information and data becoming available. Initiatives such as the International Polar Year and ArcticNet have allowed for an enormous increase in Arctic research resulting in the production of large amounts of new information and data that are important for Inuit. Led by Inuit Qaujisarvingat: Inuit Knowledge Centre (IQ), the research centre at Inuit Tapiriit Kanatami (ITK), the goal of this project is to develop and maintain an Inuit-specific integrated information management system (IIMS) that supports the ethical collection, discovery, preservation and use of Inuit knowledge and provide access to this information. This project would first identify Inuit needs for environmental, cultural, socio-economic, human health, and other data as well as requirements to develop new ways to manage, interact and share information. Members of the team will consult, develop options, and implement them to meet the needs of all stakeholders (including Northern researchers and Inuit). Feedback from partners, including the Inuit Qaujisarvingat National Committee (IQNC), along with ethical and technical considerations will drive decisions on selection of processes, informational needs, methodologies, and the design of tools. Recognizing that information resources are available from a wide range of sources and locations, and that establishing a ‘central repository’ may be neither desirable nor feasible because of the dispersed nature of Inuit communities and regional initiatives, we will focus on building a distributed model with interoperability at its core. IQ will initially focus on: (1) Procedural tools, (2) Database of funded Arctic research projects, and (3) Data sets including Bibliographic Databases, Inuit Health Data, Local Environmental Knowledge Data. These are areas identified as priorities by the IQNC, are in keeping with the interests of ArcticNet’s mandate, address the priorities of Canada’s Northern Strategy, and connect Inuit interests at the community, regional, national, and international level. Success measures for this project would be the development of an appropriate platform for the preservation, curation, and sharing of information about Inuit and the Arctic for Inuit, northern researchers, educators, policy- and decision- makers at the community, regional, national and international levels. The development of this IIMS will give Inuit and Northern researchers in Canada and abroad the appropriate levels of data and information required to prepare for the changes to their world. Further, Inuit and Northern researchers will be brought together through the co-production of new and clearly articulated knowledge and processes to access and share information as well as through the production and use of new online tools and communication networks that would grow throughout and beyond the duration of ArcticNet.

KEY MESSAGES

- To improve connections between Inuit and Arctic researchers, this project has allowed us to expand and foster partnerships to take advantage of expertise in the areas of knowledge, training, data management, and the development of further funding proposals.
- Supporting Inuit-specific research and providing access to Inuit data and knowledge situates IQ as a focal point for knowledge sharing from which to inform sustainable arctic policy.
- Given the growing international data management movement, Inuit, and Inuit representative organizations stand to benefit from being engaged through the development, use and maintenance of an Inuit-specific integrated information management system (IIMS) that supports the ethical collection, discovery, preservation and use in the coproduction of Inuit and scientific knowledge.
- IQ and the Polar Data Catalogue (PDC) team and management committee are committed to working together to ensure Inuit needs and interests are incorporated into a fully functioning PDC, including PDC-lite and search functionality.
- Through the IQ website and Resource Centre, we collect, preserve, share and connect complex data sets and documentation informed by Inuit knowledge and Arctic community-based research and supportive of key priorities of Inuit.
- In an effort to make more Inuit-specific reports, publications and grey literature publicly available, IQ is establishing a bibliographic database and associated protocols as well as refining methods for conducting systematic literature reviews on subjects of importance to Inuit.
- In direct response to the growing demand for Inuit involvement in arctic research, IQ is building a more effective and efficient system to streamline the research request process among Inuit organizations and arctic researchers.
- As there is no central database that monitors and provides the specific details of funded arctic research projects, IQ is bringing forth Inuit interests to explore the feasibility of building such a platform.
- Given the popularity of *Naasautit* as a user-friendly online resource, IQ will continue to investigate appropriate processes and systems that build on the technical framework in order to expand and make available important Inuit health data sets.
- Using the Circumpolar Flaw Lead Team 10 data and the Inuit Land Use Occupancy Project (ILUOP) as case studies and in collaboration with Inuvialuit partners, IQ facilitates the exchange of Local Environmental Knowledge information analysis, access, preservation and discovery within and between Inuit Regions, as well as with the academic community to develop innovative forms of coproduced knowledge.

OBJECTIVES

1. Build on previous and ongoing consultations with Inuit and non-Inuit partners, including international aspects, to expand the information and technical network, and to operationalize these relationships (i.e., data sharing infrastructure and agreements, MoUs, develop methodologies and processes, etc.).
2. Conduct environmental scan and needs assessment with Inuit and non-Inuit partners, on the following: (a) service needs, (b) informational needs, (c) process needs, and (d) structural needs.
3. Consult with Inuit and non-Inuit partners on the development and operationalization, in participation with ArcticNet researchers, of an Inuit-specific process for responding to

outside information and research requests (including research support letters).

4. Investigate feasibility of establishing a database of funded Arctic research projects, through discussions with representatives of larger Arctic research programs and PDC partners.
5. Operationalize data discovery and documentation systems developed through previous ITK and IQ projects starting with: (a) bibliographic documentation, (b) Inuit Health Data (Naasautit informational database), (c) Local Environmental Knowledge Data (the International Polar Year funded Circumpolar Flaw Lead project, and the Inuit Land Use and Occupancy Project).
6. Train IQ staff on information management techniques, tools, upload, and data manipulation. Training to come from external and internal IM/IT partner expertise, including the PDMC and our Research Fellow from Exchange for Local Observations and Knowledge of the Arctic (ELOKA).
7. Establish selected data stores to move towards our goal of developing and maintaining existing systems: website, bibliographies, resource centre and databases. Build on existing connections with the PDC and data/information resource documentation and sharing.

INTRODUCTION

The Arctic is rapidly changing from the effects of climate change, resource development, and globalization. These changes emphasize the need for knowledge sharing among Northern researchers and Inuit to identify strategies for adaptation, sustainable development, and governance to benefit all Canadians. ArcticNet's Strategic Plan for the second funding cycle (2011-2018) has evolved to forge the much-needed alliance between researchers and Inuit in the study of the changing Arctic. Inuit representatives on the ArcticNet Board of Directors, the Research Management Committee, the Inuit Advisory Committee, and support for the Inuit Research Advisors have ensured Inuit involvement in the Network. This alliance has also been ensured through the support of Inuit Qaujisarvingat (IQ), the research centre at ITK. The mission of IQ is to lead efforts to ensure an increasingly active role for Inuit in research that leads to the generation of innovative knowledge for improved research, science, and policy decision-making within a Canadian, circumpolar and global context. Immediate priorities of IQ are to invest in and build research capacity, and improve research connections within and between IQ, Inuit organizations and Northern researchers. This mission to support Inuit-specific research and improve access to Inuit data and knowledge will situate IQ as a focal point for knowledge sharing from which to inform sustainable arctic policy. Crucial to the IQ is establishing the infrastructure and data management needs in a strategic way, which includes mechanisms to assist Inuit and their representative organizations in identifying their information and research needs. The goal of this project is to develop and maintain an Inuit-specific integrated information management system (IIMS) that supports the ethical collection, discovery, preservation and use of Inuit knowledge and provides access to this information. Recognizing that information resources are available from a wide range of sources and locations, and that establishing a 'central repository' may be neither desirable nor feasible in all situations because of the dispersed nature of Inuit communities, and regional initiatives, we will focus on building a distributed model with interoperability at its core. This project first identifies Inuit needs for environmental, cultural, socio-economic, human health, and other data sets as well as requirements to develop new ways to manage, interact and share information with each other. Members of the team will continue to consult, develop options, and implement the most appropriate option to meet the needs of all stakeholders. Feedback from partners, along with ethical and technical considerations drive decisions on selection of processes, informational needs, methodologies, and the design of tools. Previous ITK reports revealed many possible information resources of importance (Canadian Cryospheric Information Network, government sources, Inuit Organizational sources, Spatial Data Inventories, Polar Data Catalogue, etc.). IQ is, therefore, endeavoring to include a large number of sources and to make these resources available to a wide range of users while respecting access/consent models established by resource holders. This project is focused on developing information technology infrastructure (physical, policies, procedures, etc.) to support the overarching goal of making Inuit knowledge more accessible to science/policy-makers and making science/policy resources more accessible to Inuit and their representational organizations.

ACTIVITIES

The following is a list of activities carried out by the project members this year that were funded through this ArcticNet project as well as related activities that, while funded by other sources, directly relate and contribute to this project and its objectives. The activities are broken down into five categories: Relationship Building, Integrated Information Management System, Procedural Research Tools, Database of funded Arctic research projects, and Data Sets.

Relationship Building

- Throughout the year the Inuit Qaujisarvingat National Committee (including members from Nunatsiavut Government, Makivik Corporation, Nunavut Tunngavik Inc., Inuvialuit Regional Corporation, ICC-Canada, National Inuit Youth Council, Pauktuutit, and ITK) was engaged to provide feedback, comments and direction on the development of all aspects of this project. This included numerous teleconference calls and face-to-face meetings. When possible, in-person meetings were scheduled to correspond with large conferences and meetings to ensure that all IQNC members were in attendance and had the opportunity to participate in larger events. In addition, beginning in September 2014, in an effort to streamline the sharing of materials IQ began disseminating Monthly Communique email.
  - » Face-to-face meetings included:
    - March/April 2014 in-person meeting Ottawa, ON.
    - October 2014 in-person meeting Quebec City, QC in conjunction with the Inuit Studies Conference.
    - December 2014 in-person meeting Ottawa, ON in conjunction with the Arctic Change 2014 conference.
  - » Teleconference calls included:
    - September 2014 Arctic Inspiration Prize review and adjudication.
    - November 2014 Aboriginal Peoples Survey.
    - January 2015 Resource Centre Strategic Plan review and approval.
- On a quarterly basis, prior to each ITK Board of Directors meeting, IQ developed a detailed report to update the Board via the ITK Executive on many facets of this larger project.
- Within ITK, IQ maintains close connections with each of the departments and centres. This includes the Amaujaq Centre and the National Committee on Inuit Education by attending their in-person meeting in April 2014. In addition, IQ supported the joint ArcticNet-Amaujaq call for Research on Inuit Education, as well as the Inuit Education sessions at Arctic Change 2014. IQ also continued to strengthen connections with the Department of Health and Social Development (DHSD) and the National Inuit Committee on Health (NICoH) including supporting the Request

for Expressions of Interest to the Pathways to Health Equity for Aboriginal Peoples (Pathways), a Canadian Institutes of Health Research (CIHR) Signature Initiative in June 2014.

- Throughout the year, IQ partnered with Université Laval professor Thierry Rodon, and Carleton students to work on Tukitaarvik: Inuit Student Centre (www.tukitaarvik.ca). This is a component of a larger ArcticNet funded education project (*Improving Access to University for Inuit Students*), and IQ is responsible for administering the website. This also included a brief project team meetings during the Inuit Studies Conference and the Arctic Change 2014 Conference, where some filming was done.
- Throughout the year IQ has collaborated on the ArcticNet funded project *IRIS Process as a Science-Policy Mechanism: A Case Study of IRIS 4 in Nunavik and Nunatsiavut*. This involved conducting interviews, verifying transcripts and preparing for analysis.
- Throughout the year IQ has maintained strong connections with the Canadian High Arctic Research Station (CHARS) development and planning. IQ activities include: regular participation on the CHARS Management Committee and assisted in the establishment of the CHARS Inuit Advisory Committee; assisting with CHARS priorities; assisting in the development of a CHARS Call for Proposals; collaborating on the development of a draft Future Health and Wellness Conceptual Framework and Traditional Knowledge Conceptual Framework for the Canadian High Arctic Research Station; coordinating an Inuit-specific review of the draft Data Policy. In addition, IQ assisted in briefing Terry Audla, ITK President for his appearance at Senate regarding CHARS.
- Throughout the year IQ continued to foster a relationship with Oceans North Canada and develop ideas around partnering on a shipping project. This is a new partnership for ITK that has resulted from the capacity built through this project.
- Throughout the year IQ has met with DHSD to discuss improving Inuit access to health information through Emapping. Areas of interest and exploration have been Food Security, Oral Health, and Social Determinants of Health.
- January-May 2014: Scot instructed *GEOG 4022A: Seminar in People, Resources and Environmental Change*, a 4th year course at Carleton University, Department of Geography, & Environmental Studies. In small groups the students acted as consultants to ITK working on Traditional Knowledge, Food Security, and Wildlife Management. Throughout the course IQ facilitated the collaboration between the student groups and ITK file leads. Through this relationship with Carleton University, IQ assisted in bringing a practicum student, Shannon Scodnick, to ITK to assist with the Department of Environment and Wildlife's work on polar bears (see below under Local Environmental Knowledge Data for more details).
- March-May 2014: IQ went through a hiring process to fill two positions within the centre. With the departure of Martin Lougheed to pursue other opportunities in Nunatsiavut, the Research Analyst position was filled by Jesse Flowers. A new position of Resource Centre Librarian was created to develop and implement a plan to manage the physical and digital information holdings for ITK. This position was filled by Helen Halbert.
- May-September 2014: IQ brought on Caitlyn Baikie as a summer student to assist with priority files for the department. Caitlyn, originally from Nunatsiavut, is currently an undergraduate student at Memorial University.
- June 2014: IQ in collaboration with the IQNC submitted a Session Proposal to the International Conference on Arctic Research Planning (ICARP) III as part of the 2015 Arctic Social Science Week in Japan. Scot was to be the main

convener and the session would be designed to present some of the recent Inuit-specific experiences, interests, and emerging processes related to ever-evolving Arctic research and policy landscape in Canada. This session would highlight some of the challenges and solutions in bridging scientist-Inuit partnerships so that they are constructive and mutually beneficial. Unfortunately, due to the volume of proposals received, this Inuit-specific session was merged with other proposed sessions to create "Co-design, co-production, co-communication of scientific knowledge–how to frame concerted research for sustainable development in times of change" which will be broader than Canadian Inuit-specific.

- June 2014 and February 2015: IQ met with representatives from Statistics Canada's Aboriginal Statistics Program to discuss ITK engagement in Statistics Canada's aboriginal data initiatives. A June meeting also served as a meet-and-greet for Jesse as the newly-hired research analyst to establish a stronger working relationship with StatsCan analysts.
- August 2014 (ongoing): IQ worked on establishing research bottom lines and partnership principals to assist in guiding the work with Researchers and in establishing meaningful partnerships. This was done in two sections - Elements of a Collaborative Research Proposal and Inuit Expectations for Engagement in Research Partnerships. These documents were shared with the National Inuit Committee on Health and the IQNC.
- August 2014 (ongoing): Through networks fostered by this project, IQ collaborated and is a co-applicant on the submission of a large SSHRC Partnership Grant led by Jackie Dawson (University of Ottawa) entitled Arctic Marine Use and Transportation Project (AMUT). This project brings together partners and co-applicants including key academics and other collaborators, such as industry, and government both nationally and internationally. This project is designed to respond directly to challenges through a partnership project that will: detail current and future use of the marine environment in Arctic Canada, identify opportunities and risks for the nation, and help to establish urgently needed policy options for effective Arctic marine governance.
- September-December 2014: IQ assisted Kendra Tagoona, the ITK lead Project Coordinator ArcticNet with her role in planning for the Arctic Change 2014 Conference. This included logistics and planning support leading up to the conference by helping to review the package for Inuit participants.
- September 2014 (ongoing): IQ has been collaborating with the Department of Health and Social Development (DHSD) to develop an Inuit-specific digital collection of research and information related to early childhood development.
- October 2014: Scot, Carrie, Helen, Jesse and Karen attended the Inuit Studies Conference in Quebec City. The Inuit Studies Conference takes place every 2 years and is an excellent opportunity for staff to learn, network, as well as discuss Inuit-specific information.
- October 2014 (ongoing): IQ staff and collaborator Peter started engaging with a number of polar data management organizations, including CCIN/Polar Data Catalogue, Centre d'Études Nordiques, Carleton University, Aboriginal Affairs and Northern Development Canada, and others on the possible submission of a Canadian Foundation for Innovation proposal under their Cyberinfrastructure Initiative. This has resulted in a number of conference calls and e-mail exchanges. Discussions are ongoing and IQ is considering becoming a co-applicant or collaborator on a proposal.
- November 2014: Jesse took part in an all-day Statistics Canada Aboriginal Research Network Workshop at the Wabano Centre for Aboriginal Health in Ottawa. This initiative, organized

by Statistics Canada, was meant to share with National Aboriginal Organizations (NAOs) their recent analyses, works in progress and to discuss emerging issues.

- December 2014: Scot, Carrie, Helen, Jesse, Peter and Karen attended the Arctic Change 2014 Conference. This was an opportunity for us to become more familiar with ArcticNet as well as build upon existing and establish new research relationships. During the Conference IQ staff:
  - » were present at the ITK Booth to inform participants about the Centre and about the work we are doing under this project;
  - » attended various meetings including the Polar Data Management Committee Meeting, CACCON meeting, CNNRO meeting, Tri-council data management initiative meeting and CHARS meeting as part of the Arctic Change 2014 Conference; and
  - » Karen presented Nilliajut: Inuit Perspectives of Security, Patriotism and Sovereignty as part of session T07 Arctic Security, Arctic Uncertainty, Arctic Complexity: Learning from the Past, Anticipating the Future.
- December 2014-February 2015: IQ interviewed select ITK staff and began consultations with IQNC committee members about their information needs in order to identify possible access options (e.g. consortia pricing) for Inuit partners to paywalled/by-subscription research databases.
- January 2015 (ongoing): IQ has been corresponding with researchers from Carleton University and Concordia University to explore potential connections to their five year action research SSHRC project. This project is focused on Inuit in Montreal and Ottawa and as part of it they are interested in gaining access to ITK archives.
- January 2015 (ongoing): IQ welcomed a Carleton University practicum student, Amy Prouty, who will be working on a number of initiatives including the development of an online knowledge base for IQ's website.
- IQ continued to connect and build partnerships with numerous bodies and attended meetings such as:
  - » July 2014: Inuit Circumpolar Council General Assembly (Inuvik)
  - » August 2014: Carleton University Institute on Aboriginal Research Ethics (Ottawa)
  - » October 2014: Polar Code Session (Ottawa)
  - » October 2014: North American Association of Environmental Educators Conference (Ottawa)
  - » October 2014 and March 2015: Government of Canada's Aboriginal Information Management Committee meeting in Gatineau
  - » November 2014: Nunavut Library Association meeting at the Nunavut Legislative Library (via teleconference)
  - » November 2014: First meeting of the IASC-SAON Arctic Data Committee (Potsdam, Germany)
  - » November 2014: ELOKA Advisory Committee Meeting (Pine Ridge, South Dakota) (via teleconference)
  - » February 2015: Forum on Science and Evidence-based Decision-making (Toronto)

Integrated Information Management System

- IQ has established a metadata sharing link with the Polar Data Catalogue (PDC). Using software developed and reported in previous years, IQ can now readily harvest metadata records from the PDC. Sharing of information between the PDC and IQ infrastructure has been enabled through the use of the Open Archiving Initiative Protocol for Metadata Harvesting (OAI-PMH). This is a widely adopted protocol that allows for data exchange with hundreds of possible metadata catalogues using OAI-PMH. The protocol supports the transport of many metadata formats including FGDC (used by the PDC), and ISO 19115 (used by many polar data centres). With the technology developed to harvest records from the PDC, IQ is now in a position to harvest metadata records from other relevant catalogues.

- IQ staff are working internally and with PDC staff to establish a set of PDC records that are of specific interest to ITK and its partners. Only this subset of records will be harvested from the PDC. Additionally, as part of the design process, a template has been developed to display appropriate fields of information from PDC records on the IQ website. Colin, as technical staff has been brought on and is finalizing the quality control and assurance process for the Circumpolar Flaw Lead System Study Team 10 (CFL T10) data held by IQ. Upon completion, a series of CFL T10 metadata records will be created and submitted to the Polar Data Catalogue. These will be the first records harvested from the PDC and used with the IQ Website in a simplified form with a link back to the full record in the PDC.
- The OAI-PMH harvesting tool is standards-based and flexible and thus metadata can be harvested from many catalogues. Right now, the harvesting is done manually by staff but there is hope to have the system developed to be able to retrieve records automatically. The next target for harvesting is the ELOKA catalogue hosted at the National Snow and Ice Data Center.
- The IQ website is built using a content management system (Drupal). The software developed to harvest from the PDC creates information objects within Drupal that can be reused throughout the website, for example in display forms. We are designing and testing display forms to ensure the best possible experience for IQ site users.
- December 2014: The Polar Data Management Committee (PDMC) had a meeting at the ArcticNet Arctic Change Conference in Ottawa. IQ continued to lead discussions around improving PDC metadata to enhance Inuit use, including reviewing and updating the Metadata to add Inuit-specific information, and improving Geographic locations by adding "Nunavik" and "Inuit Nunangat" to the PDC Keywords list. There continue to be discussions around the need for a review of the PDClite functionality and usefulness in Inuit Nunangat, for example given limited internet connectivity, however in order to properly conduct this review dedicated funding is needed.
- Building on previous years, Peter continues to lead the development of the geographic information infrastructure housed at IQ. This included ongoing server and software maintenance and the deployment of new GIS, web mapping, and geographic ontology tools. We now have a dedicated Linux-based geospatial data server in place and operating alongside core ITK IT infrastructure. Work on adding value to the Circumpolar Flaw Lead (CFL) System study Team 10 data set continued. This infrastructure is now being used extensively by technical staff to support a number of activities related to the CFL T10 validation and QA/QC process and the development of a number of other projects including a Polar Bear Information Tool, and a series of health atlases (e-Health, Dental Health, Food Security.
- In his role as Visiting Research Fellow, Peter connects IQ to the ArcticNet funded "Inuit Knowledge and Geospatial Ontologies in Nunatsiavut" project (Chris Furgal, Tom Sheldon leads). In this project, knowledge models, visualization and geographic information tools are being developed to represent Inuit knowledge of the Nunatsiavut region. During this reporting period, the technology infrastructure at IQ was configured to allow ready deployment of the tools being developed through the Geospatial

Ontologies project. Specifically, semantic web (i.e. CMap Ontology Edition, Protégé ontology editor), visualization (D3.js visualization library), and mapping (Nunaliit Atlas development framework) tools have been installed. The latest results of the project were present at the Arctic Change 2014 conference and a journal article is in preparation (Peter L. Pulsifer et al., 2014, 2015). IQ is ready to deploy solutions developed by the Geospatial Ontology project.

- Peter attended a number of meetings and workshops related to polar data management. First meeting of the IASC/SAON Arctic Data Committee (Potsdam, Germany); the SCAR Open Science Conference (Auckland, NZ)– discussions at this meeting resulted in the establishment of the Second Polar Data Forum to be held in Canada in October 2015, of which Peter and Scot are part of the planning process; meeting to plan a data management system for the Mackenzie River Basin (Yellowknife, NWT); virtually presented on arctic data management and community based monitoring at the AMAP meeting (Whitehorse, September 2014); ISR CBM program advise on behalf of ELOKA and ITK (Whitehorse, September 2014); presentation on data management and Traditional Knowledge to the Global Human Ecodynamics Alliance and he North Atlantic Biocultural Organization (Baltimore, Maryland).
- Internal and external IT experts continued to assist in reviewing the IQ website framework, known as a Wireframe, to develop an overarching site map and infrastructure to better situate the deliverables of this project (i.e., bibliographies, resources, maps etc.). IQ continues to prioritize the website components to be updated first, as we make the larger upgrade to Drupal 7. IQ staff focused efforts on developing content for sections of the website which were deemed to be priorities, such as Research requests, information about research in Inuit Nunangat, as well as a FAQ section.
- As part of the daily operations of IQ, we are building expertise for Microsoft SharePoint for document storage and project management. IQ have met numerous times with internal and external IT specialists to discuss the usefulness and challenges of SharePoint.
- Fall 2014: The manuscript which was submitted to a special issue of the CODATA Science Journal focused on the Polar Data Forum was published (see P.L. Pulsifer et al., 2014). This was an outcome of the October 2013 attendance and presentation at the joint International Forum with the general theme of ‘Polar Data Activities in Global Data Systems’ in Tokyo, Japan, and done in collaboration with a number of other authors (including Julie Friddell of the ArcticNet funded PDC and Warwick Vincent of Laval/ArcticNet).
- September 2014 (ongoing): IQ has started exploring and evaluating a number of free technologies and tools support research, project management, information aggregation, and information dissemination. These include Trello, Yahoo Pipes, Yammer, diZapier, and MailChimp.
- September-November 2014: As part of its work to the Inuit-specific digital collection of research and information related to early childhood development, IQ developed a set of requirements and design considerations when developing information systems for Inuit-specific information and then researched and tested a suite of library software options.
- November 2014 (ongoing): In order to further assist internal ITK infrastructure needs, Jesse has taken on a minor IT role within ITK, supporting users with informatics “quick fixes” and escalating incidents to a technology consultant as required. Jesse serves as a liaison between IQ and the consultants. In addition to his Network Administrator Lite role, he is part of the Phone System team that helped to implement and manage the transition to our new VoIP telephone system, supporting internal users as required.

- December 2014-January 2015: Following the analysis of an internal IQ information needs survey, IQ researched and evaluated possible information services that could support increased awareness of relevant publications, events, and initiatives for those engaged in Inuit.
- February 2015: Jesse performed a review of several Collaboration Centre software options in order to prepare for the development of an online resource where ITK/IQ employees can share documents, discussions, and decisions with external collaborators such as our various national committees. As a result of the review we are looking at exploring the possibility of deploying a SharePoint Online intranet site that would be organized by workgroup and committee.

Procedural Research Tools

- IQ continues to develop a more formalized internal process at ITK for dealing with outside requests (i.e. review documents, letters of support, become involved in projects) with the goal of helping to connect and coordinate Inuit at the community, regional, national and international levels.
- July-September 2014: IQ in connection with the IQNC facilitated an active approach for the Arctic Inspiration Prize, putting out a call for interested applicants to connect with IQ/ITK through the online Request Process and adhere to a specific detailed set of deadlines and process. This enabled for a thorough review of all request for ITK/IQ to be engaged and for the IQNC to adjudicate and make recommendations in September via teleconference.
- Once all requests were received, in order to make recommendations on how to proceed IQ engaged the IQNC (September 2014 teleconference call). The results for this review were:
    - » ITK was Ambassador for the Hudson Bay Network (Arctic Eiders Society).
    - » ITK provided a Letter of Support to the Inuvialuit Settlement Region – Community Based Monitoring Program.
- IQ continues to promote the use of the online form which allows anyone to submit a request through the ITK website. This streamlines the request through one point of contact for the whole organization and has allowed decisions to be made more efficiently by gathering information in this standardized manner. IQ continues to be a main point of contact within ITK for requests, in this capacity IQ provides draft text for other staff to respond to external requests directing them to the online form and assists in standardizing the evaluation and review of the requests once submitted via the form. IQ carries out a preliminary Evaluation of each request and makes recommendations which are shared with the appropriate individuals including file leads and departments within ITK, the IQNC, and specific regional contacts depending on the nature of the request. For example, this year 30 requests have been received using this online system.
- Feedback from IQ and ITK partners, IQNC, committees, and other stakeholders are ongoing in order to improve the request process and its tools such as the online form, ensuring information needs and expectations of a streamlined approach are met.
- IQ staff have also begun to explore possible automation of aspects of the Research requests process through integrations with project management tools that allow staff to track, share, and re-assign requests to others when appropriate.
- January 2015 (ongoing): With the help of a master's level practicum student from Carleton University, IQ is also working to develop a basic knowledge base of Frequently Asked Questions (FAQs) received by IQ in order to decrease the time-consuming triage and processing of inappropriate but common information requests submitted to the online form. The knowledge base will be made available through the IQ website.

Database of funded Arctic research projects

- It has been a long-standing interest of IQ to develop a database of funded Arctic research projects. In previous years, through discussions with partners, it was determined that there is interest, and it would be feasible, to construct such a database. Securing funding to develop the appropriate partners, discuss the prototype, and conduct the work would assist all research programs, researchers and Inuit. This proposed project was written into the ConnectNorth proposal in 2013, a National Centre of Excellence submission, as a "Research Compendium" project. It was determined that it would be key to have a Network like this carry out the project with the academic partners, research funders, northern licensing offices and Inuit Regional Organizations all contributing to its development. Extensive planning has been put into this. Unfortunately the project was unsuccessful.
- IQ staff continue to promote the idea and need for this within its networks and partnerships including at meetings as well as attempting to include it within proposals IQ is exploring.
- This is still an ongoing project which will require dedicated time and funding to occur.

Data Sets

Bibliographic Databases

- In an effort to make more Inuit-specific reports, publications and grey literature publically available, IQ has been working on establishing a bibliographic database and associated protocols, as well as methods for conducting systematic literature reviews. The bibliographic protocol using existing software (EndNote) was developed by IQ and the team from McGill University for use in the Climate Change Adaptation Gap Analysis funded by Aboriginal Affairs and Northern Development Canada in 2011.
- This protocol has been adapted and further revised by IQ staff. All of these bibliographies were informed by the IQ protocols and are available and accessible to support the work of ITK staff.
- IQ is exploring migrating its bibliographies to Zotero, a platform offering similar functionality to EndNote but available free of charge; this move would allow greater collaboration between IQ and other ITK staff who do not have licenses for the EndNote software. IQ has also identified a handful of staff members who are willing to participate in a trial use of Zotero to see how it satisfies research management needs.
- Over many years of research, Peter has developed a bibliography focused on polar data management in general and specifically related to local and Traditional Knowledge and community based monitoring. The bibliography includes hundreds of references to peer reviewed and grey literature. Using the Mendeley citation tool, this bibliography has been shared with IQ and linked to their emerging library system (see Zotero reference above).
- January 2015 (ongoing): As part of her practicum, Amy Prouty has been conducting a literature review of the history of Inuit engagement in research as per IQ's systematic literature review protocol, as well as documenting her research process along the way.

Inuit Health Data

- IQ and the Department of Health and Social Development (DHSD) at ITK have been having collaborative meetings to discuss linkages between the departments. A large component of these meetings is Inuit Health Research and Data.
- IQ continued to support and encourage DHSD, NICoH and the Inuit Regions in moving forward activities on the Inuit Health Survey, including

the establishment of the Inuit Health Survey Working Group.

- Identified by NICoH as a priority, Martin worked on developing an Inuit Health Indicators discussion paper that is an overview of the current status (Inuit Qaujisarvingat, 2014). This paper is now complete.
- IQ provided support and review services to DHSD for the production of their paper on the Social Determinants of Inuit Health, which was released on November 19, 2014.
- IQ continues to support DHSD as they work to improve the relationship between the Canadian Institutes for Health Research and Inuit.
- Throughout the year IQ has been working on upgrading the IQ website (www.inuitknowledge.ca) from Drupal 6 to Drupal 7. Naasautit is a large component of the upgrade, and it is expected that there will be datasets available spanning two survey years (2006 and 2012) at the launch of the upgraded site.
- Building on previous years, improved relations with Statistics Canada have led to fulsome discussions on priority Inuit-specific issues and have opened the door to greater possibilities.
- May 2014: IQ obtained tables, produced by Statistics Canada with data from the 2012 Aboriginal Peoples Survey (APS). These tables were produced by request using in-kind support provided by Statistics Canada, who offer 500 person-hours per year for data production purposes. These tables are being uploaded to Naasautit.
- May 2014: Health Canada provided a briefing to ITK staff on the 2012 APS, and Inuit-specific tables as well as the from the National Household Survey.
- June 2014: Coordinated a pre-release Inuit-specific review and provided input on Statistics Canada's publication "Inuit health: Selected findings from the 2012 Aboriginal Peoples Survey, 2012".
- July 2014: Adjudicated paper titled "A neighbourhood-level analysis of colorectal cancer incidence in Ontario's Aboriginal population, 1998-2009", and declined comment as the paper was not Inuit-specific.
- July-August 2014: IQ coordinated a cross-departmental ITK review of another Inuit-specific Statistics Canada paper –"Housing and health among Inuit children"–which is yet to be released.
- September 2014: Adjudicated Statistics Canada paper titled "Labour force characteristics of the Métis: Findings from the 2012 Aboriginal Peoples Survey" as non-appropriate for Inuit-specific review.
- October 2014: Statistics Canada contacted ITK (among other NAOs) with a questionnaire meant to capture our assessment of the 2012 APS. This covered which questions worked well or not, our ranking of subject-matter areas by priority, and any other comments we may have. Jesse circulated the questionnaire amongst ITK Directors, and presented it to both the IQNC and NICoH, which led to the generation of numerous comments and responses from the Inuit perspective. This was packaged and sent to Statistics Canada, who have taken the initiative to meet with IQ in order to discuss these issues in depth.
- February 2015: IQ met with Statistics Canada to discuss the 2012 APS review.
- February 2015: IQ was approached by Statistics Canada to review an abstract and study proposal using data from the 2012 Aboriginal Peoples Survey. Thomas Anderson, the principal Statistics Canada analyst, met with Jesse and Tracy (from DHSD) to discuss the framework for the study, and accepted several ITK suggestions on variables and concepts.

- Using Statistics Canada data from various sources, production of an updated Inuit Statistical Profile has begun, with the support of the ITK President, Board of Directors and the IQNC.
- With expertise developed through Local Environmental Knowledge mapping, IQ has helped to support discussions on E-mapping for other ITK priorities.

RESULTS

Relationship Building

- Capacity within Inuit Qaujisarvingat has increased with the addition of a Resource Centre Librarian and a Research Analyst as new staff members and by bringing on students for internships and placements.
- Continued to build strong connections among Inuit partners, enhancing the incorporation of regional, national and international Inuit perspectives into evolving research agendas connecting across Inuit Nunangat as well as Arctic research broadly.
- IQ is actively pursuing negotiations to build partnerships with Academic institutions, particularly those involved in Arctic and Inuit research. Through networks fostered, research projects that complement the work under this project are being explored, such as the SSHRC proposal with the University of Ottawa.
- IQ is also actively pursuing negotiations to build partnerships with the Private Sector, particularly those involved in Arctic and Inuit research. Through networks fostered, research projects that complement the work under this project are being explored, such as a shipping project with Oceans North Canada.
- This included instructing a course at Carleton University where students completed presentations and reports to assist ITK in the areas of Traditional Knowledge, Food Security and Wildlife Management.
- Worked closely to foster Inuit engagement with the IQNC and IRAs to meet their interests in relation to Research and Information Management.
- Moved forward a number of partnerships between ITK and ArcticNet on important topics like Research in Inuit Education, Highly Qualified Inuit Personnel, the IRIS Process, and the Nunatsiavut Ontologies Project.
- Ensured Inuit interests related to research and information management are shared and heard at numerous meetings, conferences and venues including Arctic Change 2014 conference, Inuit Studies Conference, Turning Statistics into Stories Workshop, and Computer-Supported Cooperative Work and Social Computing Conference.
- Inuit are being engaged by the CHARS project team through regular correspondence and teleconferences. An Inuit Advisory Committee for CHARS has been established, and through this mechanism we are negotiating capacity for Inuit involvement. However, capacity to support this involvement is still needed.
- The research bottom lines and partnership principles are being used by multiple departments at ITK and shared externally. It is the intention that these documents will serve to be initial guidelines, or a starting point, in helping Inuit establish meaningful research relationships.
- There is an improved relationship with ITK and Statistics Canada. For example, one key outcome of the Statistics Canada Aboriginal Research Network Workshop was a clear commitment on StatsCan's part to involve NAOs much earlier in the survey design, production, and analysis stages, rather than simply providing NAOs an opportunity to review papers at the near-final stage as has historically been the case.

- Through the Research Request Process at ITK, IQ cultivated external links to a variety of audiences interested in Inuit and Inuit research. Based on these exchanges, IQ is developing a Frequently Asked Questions section for the website to address the multitude of inquiries received and broaden people's awareness of Inuit.

Integrated Information Management System

- IQ can successfully harvest metadata records from the PDC.
- Further explored with PDC partners a project to verify the PDC-lite version and search functionality is seen as successful in Inuit regions and communities.
- Further developed geographic information infrastructure being used to host data from IPY CFL Team 10 activities.
- IQ website Site Map and Wireframes was finalized using the information architecture to better situate the deliverables of this project. New IQ web content has been developed in support of the new information architecture.
- Given the technical expertise developed through this project, IQ has been brought in to assist internal IT experts in Information Management systems such as Microsoft Outlook and SharePoint.
- Following the recommendations of the Needs Assessment and Options Report, IQ moved forward internally to develop a position description for a Resource Centre Librarian and mobilize a Resource Centre Hiring Committee. Helen Halbert was hired on as the Resource Centre Librarian in September 2014.
- After evaluating the functionality of library software options, it was ultimately decided to use Omeka for the Inuit-specific digital collection of research and information related to early childhood development. Omeka is an open-source web-publishing platform adhering to metadata standards and providing easy integration with Zotero, a research management tool that can be used to maintain, generate, and share bibliographies. IQ staff has catalogued and uploaded a set of 35 collection items to the digital collection and customized and configured the Omeka interface. This demo has been presented to the Inuit Early Childhood Development Working Group.
- IQ is undertaking discussions with its Inuit regional partners in order to develop a set of MOUs or license agreements, and technical mechanisms related to access restrictions and copyright permissions for items submitted to the digital collection of early childhood development materials.
- January-February 2015: IQ has started testing and using technological tools that support RSS feed aggregation and the MailChimp e-mail newsletter tool in order to pilot an Inuit-specific information service.

Procedural Research Tools

- Research request template was developed and further adapted online. The tool was made accessible online one year earlier than initially planned for this project. Through feedback from the IQNC there were adjustments to text and the inclusion of contact information for the Inuit Research Advisors in each region was added.
- All ITK staff are being encouraged to follow the same procedure. All researchers who approach ITK are being directed to submit their request at https://www.itk.ca/rfi.
- Effectively and efficiently implemented a system from the regional to national level to review and assess potential Arctic Inspiration Prize Nominations, resulting in one ITK Nomination

and one Letter of Support, and assisting us in building a more robust process.

- ITK staff have begun using this tool based on individual training sessions, staff presentations, and promotion by IQ.
- Expanded process to Inuit Regions through IQNC members in order to increase regional use and uptake, resulting in improved information exchange. This includes specific processes for when requests are received that pertain to one Inuit region.

Database of funded Arctic research projects

- While IQ has determined that there is an interest and that this could be feasible, there is a need to bring together the appropriate partners (academic, funders, government, Inuit organizations etc.), to have significant dedicated funds, and to have a dedicated body to house and maintain the information.

Data sets

Bibliographic Databases

- Having a systematic literature review protocol and process assisted ITK staff in addressing further research issues and projects that are of interest to Inuit.
- IQ staff are well versed in collecting bibliographic references and have shared these expertise with summer students, interns and other ITK file leads.
- Databases and platforms have been explored to ensure IQ and ITK staff are inputting into a sustainable, shareable system.

Inuit Health Data

- IQ moved forward internally to fill the position of Research Analyst and mobilize Inuit-specific data. Jesse Flowers was hired on as the Research Analyst in July 2014.
- The Department of Health and Social Development benefited from the sharing of research expertise, including with regard to the Canadian Institutes for Health Research.
- Some progress has been made determining the identification of what and where Inuit health data sits, which data sets are most important to make available, and what the process will be to make these determinations.
- Contribute to the dialogue of the Inuit Health Survey (including participating in the Inuit Health Survey Working Group) as it relates to the broader research implications around ethics, agreements, and data sharing.
- A final Inuit health Indicators paper was approved and the Social Determinants of Inuit Health report was released.
- ITK and Statistics Canada have a strengthened relationship, where IQ has been able to input into survey design, review documents and communicate on a more regular basis.

Local Environmental Knowledge Data

- Colin was trained by Peter on information management techniques, tools, and data upload information particularly for the CFL project data. This represents a successful exchange of knowledge and mentoring.
- CFL data was moved from previous locations to the IQ server and verified. Thus, the CFL data are now in a form that can be used to begin exploring the appropriate sharing mechanisms of data with the Inuvialuit Settlement Region and the broader academic community. While the data set is being continuously improved, the infrastructure needed to manage and preserve the data is now

in place. Specifically, this includes a dedicated, geospatially enable relational database, geospatial web services available on the ITK Intranet, networked geographic information system tools (a number of GIS Clients), a web mapping framework, and a set of geographic concept mapping and knowledge modeling tools.

- The technical systems developed for the CFL data are now in place which can be used for other data sets and projects, including the ISR ILUOP project.
- The ILUOP project is returning Inuvialuit Traditional Knowledge in a useable format back to the region in which it was generated and will help to build capacity in the next generation of Inuvialuit youth and in the ISR.
- Mapping and Emapping have been identified as priorities for displaying and disseminating information. With expertise developed, IQ has facilitated meetings with IT experts and DHSD to evaluate possible options.

DISCUSSION

Relationship Building

Through the activities of this project and the relationships developed, Inuit are better positioning themselves to direct research and respond collaboratively. One key success, fostered through this project was connecting the IQNC to researchers and research networks including the IRAs. As with all activities undertaken at IQ, we strive to consult and seek direction from this Committee to meet their interests in relation to Research and Information Management. An example of this includes the movement towards monthly communiques to complement the two in-person meetings each year as well as teleconferences. Resulting from the capacity and relationships built through these activities, the IQNC is becoming even more organized to develop and promote Inuit-specific guidelines and strategies for all things research.

Integrated Information Management System

The continued development of an Inuit-specific IIMS will give Inuit and northern researchers in Canada and abroad the appropriate levels of data and information required to prepare for the changing Arctic. IQ has made significant progress to meet the outlined measures of success for this project by developing an appropriate platform for the preservation, curation, and sharing of information about Inuit and the Arctic for Inuit, northern researchers, educators, policy and decision-makers at the community, regional, national and international levels. Through work and connections to the PDC, we have a greater understanding for the challenges associated with IIMS and are better positioned than ever to become stewards of data for Inuit in Canada. With the expertise developed through this project, IQ and the IQNC are now better positioned to provide Inuit-specific perspectives on data and information management (interoperability and standardization) to national and international stakeholders (i.e through the Polar Data Management Committee).

Procedural Research Tools

Inuit organizations are inundated with requests to engage in research at various levels. Simultaneously Inuit are better positioned than ever to be able to coordinate and effectively lead and direct research. One method that has allowed for this increasing success is the process to evaluate incoming requests to ITK. Tools developed include an online form, a word document and an evaluative criteria and considerations guide. One key successful use of this procedure and tool was its use to evaluate the Arctic Inspiration Prize Nominations and requests two years in a row. Without the support from this procedure and tool, the amount of requests received would have overwhelmed ITK and the IQNC and would not have allowed for effective and efficient evaluations.

Database of funded Arctic research projects

There is a clear interest expressed for a centralized database of funded Arctic research projects. Through this project we brought forth Inuit interests to explore the feasibility of building a composite index of arctic research funded projects to the ConnectNorth project team. It was determined that there is an interest and that this could only be feasible with significant dedicated funds, buy-in from research funding institutions, and a dedicated body to house and maintain the information. With ConnectNorth unsuccessful in its funding proposal, IQ continues to explore other possibilities for this activity to go forward, examples include the Polar Data Catalogue, Geomatics and Cartographic Research Centre, and the Canadian Polar Commission as well as with other academic partners.

Data sets

Given the scope and complexity of the information and data sets aligned with Inuit priorities, we have learned setting up systems are complicated and requires a significant investment of time and effort. This project has increased our capacity and understanding of working with data especially with respect to bibliographic databases, Inuit health data and local environmental knowledge data. Specifically tools and processes have been created and improved to support our ability to generate, manage and distribute Inuit-specific data. This includes key successes such as systematic literature review protocol and process, coordinating Inuit input into important health data sets, work with the CFL data and developing a Polar Bear mapping tool of the 13 Canadian subpopulations.

CONCLUSION

IQ in collaboration with its partners (academic, Inuit organizations, and government) is leading efforts in innovation with respect to creating an Inuit-specific integrated information management system and frameworks for accessing information relevant to decision-makers to inform policy and strategy development. This work will also allow us to foster the development of the next generation of competent, qualified Inuit researchers and leaders. Given the unique information that ITK deals with, as a national organization, this project is allowing ITK to improve our integrated approach to store, access, archive and share information.

While certain challenges are evident (e.g. limited access to Inuit students and funding pots, competing interests between Inuit priorities and funding priorities, and a lack of access to subscription-based journals and databases), the support ArcticNet provided for this project gives IQ the flexibility to build and maintain sound research relationships and address Inuit priorities as they arise (e.g. working on the concept Highly Qualified Inuit Personnel, being a nominator for the Inspiration Prize, and assisting in the development of an ArcticNet call for Expressions of Interest for Research on Inuit Education).

Support for this project represents an achievement, putting ArcticNet at the forefront of a lasting and meaningful institutional legacy that advances Inuit and Inuit knowledge for sustainable Arctic science and policy. This project seeks to establish Canada as a world leader in recognizing the value of Indigenous Knowledge and collaborating proactively with Inuit to identify, preserve and actualize this knowledge for the lasting benefit of Arctic communities, regions, Canadians and global citizens.

Inuit will continue to be brought together through the development of new and clearly articulated processes to access and share information as well as through the production and use of new online tools and communication networks that will grow throughout and beyond the duration of ArcticNet.

As this project comes to a close, the project team sees how invaluable this funding and oppportunity has been for the IQ, ITK, ArcticNet as well as for Inuit. This partnership with ArcticNet has provided Inuit with the capacity to engage and gain expertise and become part of the solution in building sustainable Arctic research and capacity.

We had hoped to submit another proposal for the next funding cycle to build on the previous three years of investment, but found that we were ineligible to receive NCE funds. If one looks at the broad array of items touched on in this report/project they will find that a majority of our ability to continue with this broad array of activities will be significantly challenged now that this funding is over, affecting the results. We would welcome the chance to explore further funding, capacity building, and future collaboration opportunities.

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